ASSEMBLY, INTEGRATION, AND TEST METHODS FOR OPERATIONALLY RESPONSIVE SPACE SATELLITES

THESIS

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AFIT/GAE/ENY/10-M01

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THESIS

Presented to the Faculty

Department of Aeronautics and Astronautics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Aeronautical Engineering

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March 2010

AFIT/GAE/ENY/10-M01

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Acknowledgments

I would like to thank my advisor, Lt Col Eric Swenson, for his guidance throughout this project. I believe his very different perspective helped change my thought process and made this thesis a more valuable product. I would also like to thank my research sponsor, Mr. Chuck Finley, for continuing to trust in me and for providing opportunities beyond my imagination. Last but not least, I am sincerely thankful for the dedication and solid work ethic of my colleague, Mr. John DiPalma, without whom this project could not have been a success.

- Capt Lisa A. Baghal

Abstract

The focus of this research is to investigate the minimization of the traditional spacecraft (S/C) system-level Assembly, Integration, and Test (AIT) timeline to accommodate an urgent need for a space-based capability.

The reality of emerging threats to U.S. space superiority was a key motivator in the 2007 formation of Operationally Responsive Space (ORS), a joint DoD office whose mission includes the rapid exploitation of new technology and supplementing or reconstituting damaged or destroyed satellites based on current battlefield needs. The rapid deployment of a new satellite to meet the Joint Force Commander's space capability needs is referred to as the Tier-2 approach. In the Tier-2 model, only two days are allotted for spacecraft Assembly, Integration, and Test (AIT), a process that typically spans multiple years. Therefore, this type of response will require a significant departure from the current spacecraft industry's best practices and concept of operations.

To investigate their vision, ORS sponsored the Rapid AIT Demonstration – a series of short AIT trials using the Air Force Research Laboratory (AFRL) Plug and Play Satellite (PnPSat-1). During the demonstration, PnPSat-1 was assembled in different configurations and tested using multiple personnel groups of varying skill sets to investigate some of the technical and logistical challenges that face ORS.

A primary goal of the Rapid AIT Demonstration was to investigate influences on AIT timeline. By timing each trial, it was found that the primary driver to AIT duration was S/C assembly activities. The trend in assembly duration indicates the timeline is most impacted by personnel training, mix of skill sets in the assembly team, and efficiency of the assembly

procedure. Another goal of this research was to verify if the tests in Rapid AIT were sufficient to detect anomalies prior to launch. There were multiple anomalies in the demonstration, but only one was not caught during Rapid AIT. It can be postulated that most errors should be detected in pre-Rapid AIT testing.

Because only two days is given to qualification of a Tier-2 S/C, ORS plans to complete qualification tests on dedicated qualification models and on all components previous to call-up. The flight models could then be qualified by similarity to the qualification model during Rapid AIT. Conclusions from the Rapid AIT Demonstration test data could support qualification by similarity and the reduction of tests conducted at the system level. Existing thermal and structural models were updated to predict the thermal properties and center of gravity location of various S/C configurations. The updated model predictions were within standards of accuracy, and were created within hours or days, versus months. These results indicate that well-tuned analytical models of the qualification model can be quickly updated to accurately predict properties for a variety of S/C configurations. This could provide some confidence in a S/C design without extensive testing.

Finally, an extensive list of lessons learned from the Rapid AIT trials have been compiled for incorporation into Tier-2 concept of operations. For example, it was found that the number of personnel on the AIT team was less important than the correct mix of skill sets, and that the personnel should have well-defined roles. Also, automation, software configuration control, and situational awareness among team members are critical to decreasing the AIT duration.

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Acronym List

ADCS	Attitude Determination and Control Subsystem
AEF	Aerospace Engineering Facility
AFRL	Air Force Research Laboratory
AIS	Automated Identification System
AIT	Assembly, Integration, and Test
ASIM	Appliqué Sensor Interface Module
CAD	Computer Aided Drawing
CG	Center of Gravity
CMD	Command
CSS	Coarse Sun Sensor
DITL	Day in the Life
DMS	Data Management System
DoD	Department of Defense
EGSE	Electronic Ground Support Equipment
EMC	Electromagnetic Compatibility
EPDS	Electrical Power and Distribution System
EPS	Electronic Power System
ESM	Energy Storage Module
ESPA	Evolved Expendable Launch Vehicle Secondary Payload Adapter
ETTI	Environmental Test Thoroughness Index
FCT	Factory Compatibility Test
FM	Flight Model

FSW	Flight Software
GNC	Guidance Navigation and Control
GSE	Ground Support Equipment
HCB	High Power Circuit Breaker
HWIL	Hardware in the Loop
IMU	Inertial Measurement Unit
JFC	Joint Force Commander
L/V	Launch Vehicle
LAI	Lean Aerospace Initiative
LEO	Low Earth Orbit
MDF	Mission Degrading Failure
MGSE	Mechanical Ground Support Equipment
MIL-STD	Military Standard
MLB	Motorized Light Band
MOA	Memorandum of Agreement
NRL	Navy Research Lab
ORS	Operationally Responsive Space
PnP	Plug-and-Play
PnPSat	Plug-and-Play Satellite
QA	Quality Assurance
QM	Qualification Model
RF	Radio Frequency
RPB	Reconfigurable Processing Board

RS7	Responsive Space 7 Conference
RSATS	Responsive Space Advanced Technology Study
RST	Responsive Space Testbed
RTC	Real Time Clock
RV	Space Vehicles Directorate
S/C	Spacecraft
SA	Solar Array
SAC	Solar Array Controller
SAR	Synthetic Aperture RADAR
SDM	Satellite Data Model
SMAD	Space Mission Analysis and Design
SMS	Structures and Mechanisms
SPA	Space Plug-and-Play Avionics
SpW	SpaceWire
TLM	Telemetry
TTC	Telemetry, Tracking and Command
TVAC	Thermal Vacuum Test
UHF	Ultra High Frequency
USB	Universal Serial Bus
xTEDS	Extensible Transducer Electronic Data Sheet

ASSEMBLY, INTEGRATION, AND TEST METHODS FOR OPERATIONALLY RESPONSIVE SPACE SATELLITES

1. Introduction

The focus of this research is to investigate the minimization of the traditional spacecraft system-level Assembly, Integration, and Test (AIT) timeline to accommodate an urgent need for a space-based capability. The Operationally Responsive Space Office (ORS) was created in 2007 to provide this capability in response to a Joint Force Commander's needs. This chapter first provides background on the ORS mission and goals, spacecraft AIT processes, and Plug-and-Play (PnP) technology. Following this background information, the problem description and motivation for this research is given. And finally, an outline of the thesis is provided at the conclusion of the chapter.

1.1 Background

1.1.1 Operationally Responsive Space

ORS is a joint office reporting to the Office of the Secretary of Defense, born from emerging threats to U.S. space superiority such as China's 2007 successful anti-satellite weapon test and GPS jamming [1]. Space systems can be a force-multiplier, providing intelligence, communication, and navigation capability. The current Presidential administration supports the need for ORS as is evident from this quote on the White House website [2]:

> The full spectrum of U.S. military capabilities depends on our space systems. To maintain our technological edge and protect assets in this domain, we will continue to invest in next-generation capabilities such as operationally responsive space and global positioning systems. We will cooperate with our allies and the private sector to identify and protect against intentional and unintentional threats to U.S. and allied space capabilities.

ORS is charged with providing "assured space power focused on the timely satisfaction of Joint Force Commanders' (JFC) needs" [3]. To meet the JFC needs, ORS envisions three possible approaches: employing current systems (Tier-1), deploying new systems with current technology (Tier-2), or developing new technology (Tier-3), as illustrated in Figure 1. This research focuses on Tier-2 type solutions.

Tier-2 solutions utilize field-ready capabilities from a complete system, series of components, or combination thereof. The targeted timeframe for delivering usable Tier-2 solutions is days-to-weeks from the time at which the need is established. The focus of activities in Tier-2 solutions is on achieving responsive exploitation, augmentation, or reconstitution of space force enhancement or space control capabilities through rapid AIT, and deployment of small, low cost satellites.

The 7-day Tier-2 timeline goal, outlined in Figure 2, only allows two days for AIT. Therefore, a Tier-2 response will require departure from the current space industry's best practices and concept of operations. Some of ORS's ideas for reducing timeline from call-up to launch include: enforcing interface standards, increasing modularity, extensive component-level qualification testing, and minimizing system-level testing. This research focuses on ways to minimize system-level testing timeline.

ORS envisions their rapid satellite response facility, currently referred to as "Chileworks," to function more like an aircraft depot than a one-of-a-kind satellite AIT facility [3] where there are a given number of platforms and sensor packages available. The example shown in Figure 3 draws a parallel between the U-2 platform with its many sensor packages and an ORS spacecraft (S/C) bus with its many payload options.

The end-state goal for Chileworks is to have steady-state and surge capabilities by 2015. During steady-state operations, exercises and testing should be ongoing to maintain AIT-ready parts and personnel. The surge response will depend on assessed threat level. To meet these goals, component inventory will be required to accommodate production of one satellite per week, or a small constellation within one month [3].

ORS's baseline concept of operations to meet these production goals includes a fully qualified component stock and a selection of qualified satellite bus designs. To investigate their vision, ORS sponsored the Rapid AIT Demonstration – a series of short AIT trials (3-5 days) using the Air Force Research Laboratory (AFRL) Plug and Play Satellite (PnPSat-1). The goal of the Rapid AIT Demonstration is to investigate AIT methods which reduce the Rapid AIT timeline to suit Tier-2 constraints. The following section will introduce basic AIT concepts, while Chapters 2 and 3 provide an in-depth discussion on AIT methods that can be applied to ORS S/C.

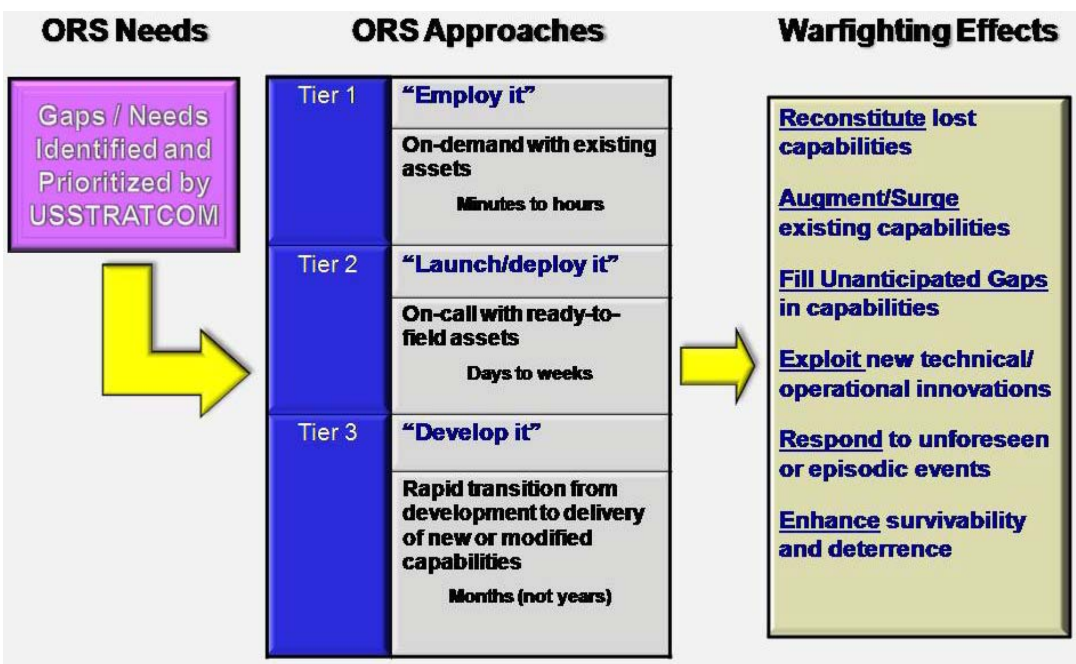

Figure 1. ORS Approaches to Meeting Warfighting Needs [3]

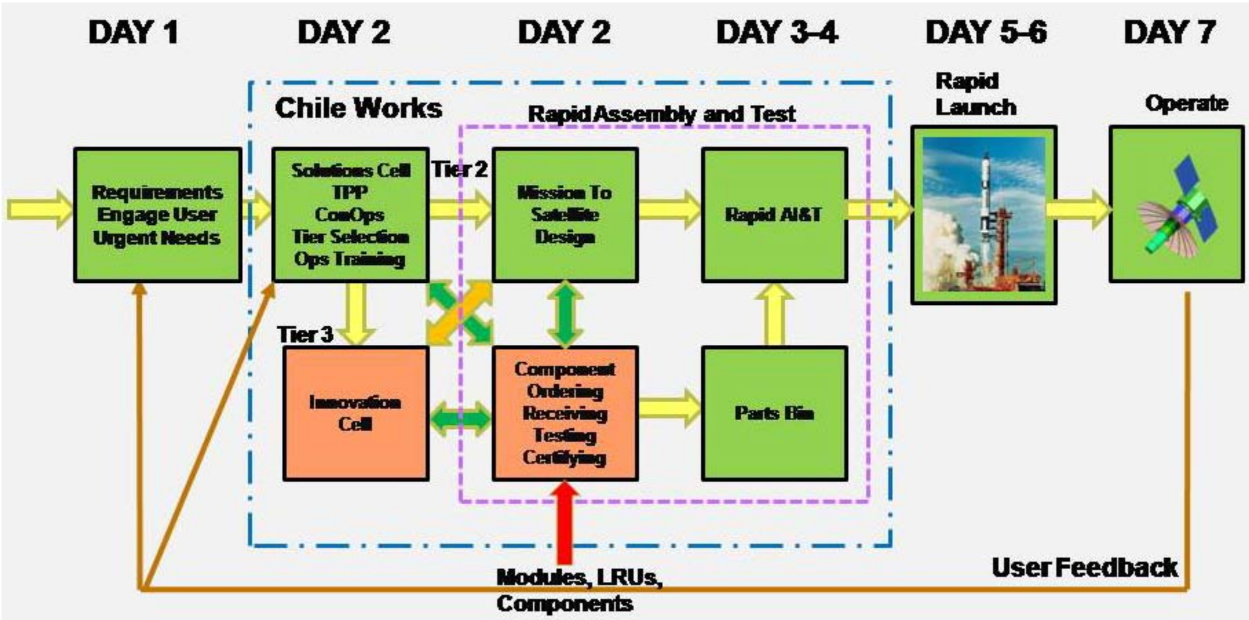

Figure 2. ORS Tier-2 Timeline [4]

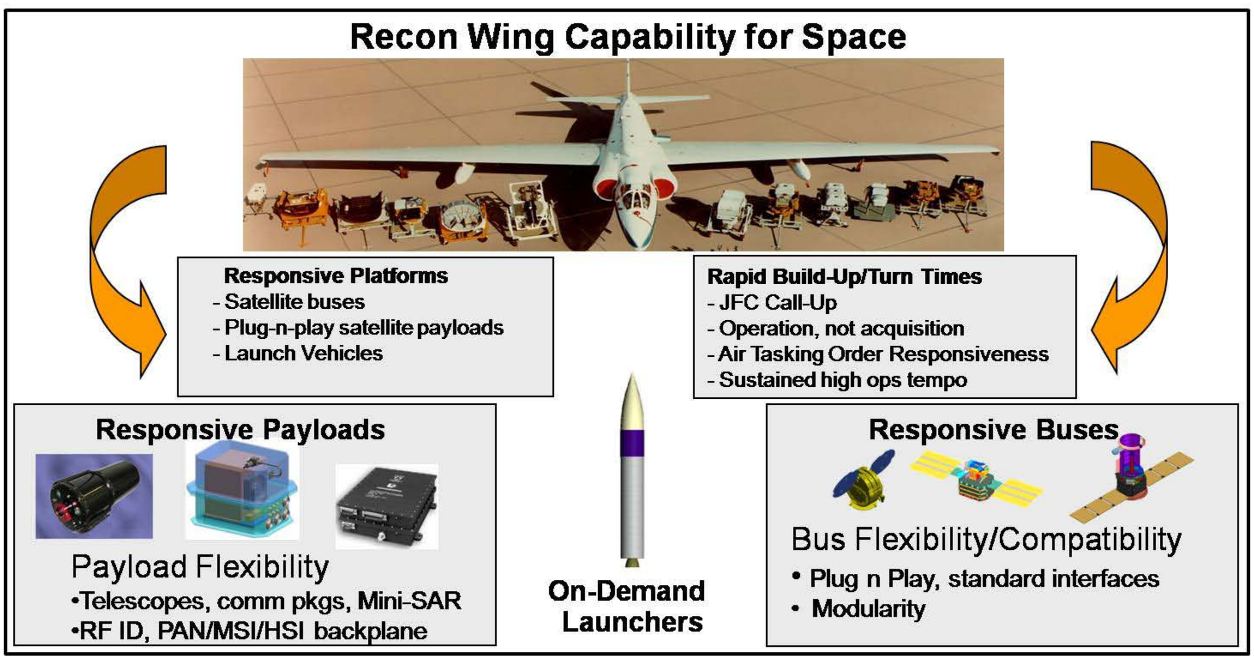

Figure 3. Aircraft Depot Model for Satellites [3]

1.1.2 Assembly, Integration, and Test

AIT is the process in which subsystems are integrated together to form a system, i.e. a spacecraft. AIT is a documented, formal, and sequential process of integrating and testing components/subsystems and the system to verify specifications and requirements are met [5]. A successful AIT process depends on a well developed test plan, created to outline how each requirement is going to be verified. The test plan should include tests/activities to identify unanticipated interactions among the subsystems, failure modes and recovery procedures, faulty workmanship, and prevent infant mortality (burn-in or wear-in tests). When deviations or anomalies occur, discrepancy reports are written to identify the problem and facilitate a solution. The entire AIT phase for a unique S/C can last many years and includes extensive performance testing – called qualification tests.

Tests are designed to replicate the actual operational environment and scenarios when possible. The vibration and thermal vacuum tests are designed to replicate the launch and on-orbit environments, respectively. Other tests for payloads, electromagnetic compatibility (EMC), and attitude determination and control subsystem (ADCS) may require the use of simulators or modeling when realistic test methods are not feasible.

The culmination of the AIT phase is transportation to the launch site, where additional tests may be necessary to verify the spacecraft survived the shipment from the integration facility. Testing may continue after the spacecraft is mated to the launch vehicle, but not for the purposes of validating design. These tests are typically called "aliveness tests" and only verify the system has basic functionality. Special safety conditions will be in place during these activities due to launch vehicle requirements.

In the baseline ORS concept of operations, all components, subsystems, and bus configurations must pass all qualification tests to be accepted into the Chileworks inventory. It will be from this stock of fully-qualified components/subsystems that a Tier-2 S/C will be assembled. Because of the previous qualification, the newly assembled S/C, or flight model, will complete only a subset of less stringent acceptance tests – called Rapid AIT. The development of the Rapid AIT test flow will be detailed in Chapter 3.

1.1.3 Plug-and-Play Technologies

In the mid-1990's, the development of the universal serial bus (USB) and Plug-and-Play (PnP) technologies for the personal computer demonstrated the possibility of simplifying complex systems such that unskilled personnel could assemble and operate them quickly. This idea, and a number of emerging experiment opportunities, inspired the Air Force Research Laboratory's Space Vehicles Directorate (AFRL/RV) to investigate PnP technologies for spacecraft [6].

AFRL/RV's PnP technology development began with projects testing new electronics and data handling approaches. Multiple experiments were flown on-orbit starting in 1995 with the MAPLE-1 experiment hosted on the MightySat-1 spacecraft [6].

In 2003, AFRL/RV began devising the first PnP architectures for what would eventually be named Space Plug-and-Play Avionics (SPA). SPA is an interface-driven set of standards designed to enable the six-day satellite. The 2004 Responsive Space Advanced Technology Study (RSATS) embraced adaptive avionics as one solution to the Responsive Space problem. Based on the RSATS results, AFRL/RV hosted eight workshops to further the advancement of the SPA technology. These workshops led to the formulation of the key SPA technology ideas: Appliqué Sensor Interface Module (ASIM), Satellite Data Model (SDM), and the Extensible Transducer Electronic Data Sheet (xTEDS). The components of the SPA architecture are described in Chapter 3.

In 2006, the Responsive Space Testbed (RST) was commissioned at AFRL/RV to continue the development of responsive spacecraft technologies. Through this effort, Plug-and-

Play Satellite 1 (PnPSat-1) (Figure 4), the first full spacecraft to implement SPA, began development in 2007. The goal of the project was to enable design, assemble, and test of a semi-custom spacecraft in 2-3 days by simplifying interfaces and hiding complexity from the user. In 2008 AFRL/RV determined that it would be too costly to flight-qualify PnPSat so it is now used as a testbed for AFRL SPA technology development and for ORS office exercises. Details of PnPSat-1 are given in Chapter 3. Work on PnPSat-2 has already begun with next generation SPA technology. However, it is unclear at this time whether PnPSat-2 will be a flight project or another testbed.

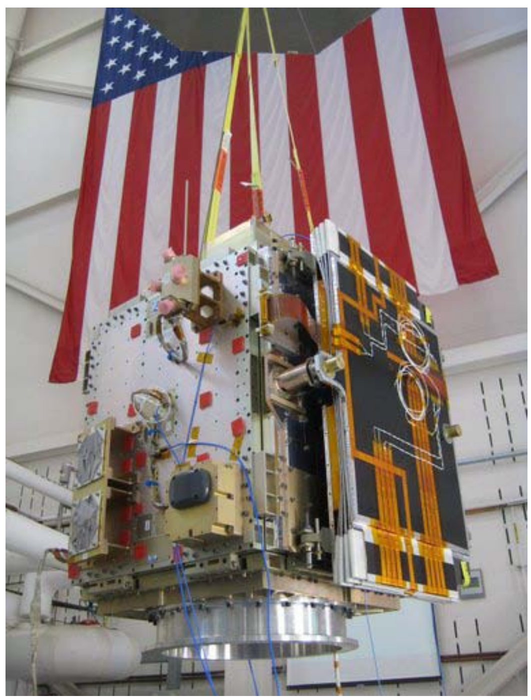

Figure 4. PnPSat-1

1.2 Problem Description

To meet current government and industry spacecraft standards, resulting AIT timelines are greater than 6 months and sometimes as long as multiple years. A typical Thermal Vacuum (TVAC) test requires several days and sometimes weeks alone. Meeting all AIT standards within the ORS Tier-2 goal to deploy a satellite within 6 days is not possible. To take a closer look at the challenges of reducing the AIT timeline, ORS has sponsored the Rapid AIT Demonstration at Kirtland AFB, NM. The focus of this research is to investigate approaches to minimize the traditional spacecraft system-level AIT timeline to accommodate an urgent need. The research goal is to provide ORS a set of data-supported suggestions and lessons learned that can be incorporated into the design of their Chileworks operation.

1.3 Motivation

As described in Section 1.1.1, the ORS office faces a challenge in developing their Chileworks facility and processes. The typical multi-year AIT timeline must be reduced to 2-3 days, which will require a significant paradigm shift. Because a single TVAC test requires more than the AIT time allotted, it is obvious that the area of testing will be of huge concern. However, it would be hasty to eliminate the TVAC test without due investigation. The results of the Rapid AIT Demonstration can provide a basis for the change ORS requires.

1.4 Outline of Thesis

Chapter 2, Satellite AIT Practices, is divided into 3 sections. Section 2.1, Traditional Spacecraft Testing, describes the industry-accepted standards for spacecraft AIT, as well as some studies into the effectiveness of these standards. Section 2.2, Rapid Satellite Production Examples, and Section 2.3, Applicability of Lessons Learned to ORS, review the examples from the space industry of rapid production and discusses the applicability of these lessons to the ORS concept.

Chapter 3, Rapid AIT Demonstration Description, details the development of the Rapid AIT Demonstration test plan in Section 3.1. Lessons learned from the background review in

Chapter 2 are utilized in the test plan development. Section 3.2 describes the PnPSat-1 test article and its limitations with respect to this demonstration.

Chapter 4, Results and Analysis, provides a detailed summary of each trial in the Rapid AIT Demonstration, to include the objectives and outcomes, in Section 4.1. Section 4.2, Test Results, gives an analysis of the quantitative environmental test data collected in the trials. And finally, Section 4. 3, Lessons Learned, will detail the suggestions of the demonstration team for incorporation into Tier-2 ORS operations. The lessons learned are grouped into the areas of spacecraft design, facility and equipment, personnel and processes, payload integration, and ground system and operations.

Finally, Chapter 5, Conclusions and Future Work, provides the conclusions of the research in Section 5.1, followed by recommendations for continued research in this area in Section 5.2.

2. Satellite AIT Practices

This chapter first reviews traditional satellite AIT practices, including military standards and industry accepted guidelines. These standards and guidelines served as the basis from which the Rapid AIT Demonstration test plan was created. Following the review of traditional practices, examples from the space industry where the AIT process has been modified to reduce timelines are presented. These example programs can provide lessons learned which are applicable to the ORS goals and constraints, and are summarized in the last section of this chapter.

2.1 Traditional Spacecraft Testing

The U.S. Department of Defense (DoD) spacecraft test programs are governed by the Military Standards (MIL-STD), MIL-STD-1540 [7] and MIL-STD-340 [9]. These MIL-STDs describe the methodology of designing a test program and specifics on test operations. Guidelines for spacecraft manufacture and test can also be found in various texts such as *Space Mission Analysis and Design* (SMAD) [8], an industry-accepted text describing best practices for space systems design, manufacture, and test, and *Space Systems Fundamentals* [5]. Guided by these documents, this section first provides the definitions of some industry-accepted terms used frequently throughout the thesis. Then, a brief description of the standards and guidelines are given, and multiple studies of the effectiveness of these testing standards are examined.

2.1.1 Terminology

This section identifies key terms that are used frequently throughout this thesis, as defined in MIL-STD-1540, SMAD, and *Space Systems Fundamentals*.

- **Component:** *Parts that are assembled to perform a higher-level function (ex. Reaction wheel, solar array).*

- **Subsystem or Payload:** *Components that are assembled together to perform a specific function (ex. ADCS subsystem, Power subsystem, Imager optics and processing components).*

- **System:** *Subsystems that are assembled together whose overall function is to execute mission requirements (ex. Spacecraft).*

- **Qualification Tests:** *Qualification tests are conducted to demonstrate that the design, manufacturing process, and acceptance program produce mission items that meet specification requirements. In addition, the qualification tests validate the planned acceptance program including test techniques, procedures, equipment, instrumentation, and software. The qualification test baseline is tailored for each program.*

- **Acceptance Tests:** *Acceptance tests are conducted as required to demonstrate the acceptability of each deliverable item. The tests demonstrate conformance to specification requirements and provide quality-control assurance against workmanship or material deficiencies. Acceptance testing is intended to stress screen items to precipitate incipient failures due to latent defects in parts, materials, and workmanship. However, the testing will not create conditions that exceed appropriate design safety margins or cause unrealistic modes of failure.*

- **Component-Level Test:** *A test conducted on a particular unit (ex. reaction wheel).*

- **Subsystem-Level Test:** *A test conducted on a particular subsystem (ex. ADCS).*

- **System-Level Test:** *A test conducted on the entire spacecraft assembly (ex. Mission scenarios).*

- **Qualification Model (QM):** *A qualification model is a complete spacecraft produced from the same drawings, using the same materials, tooling, manufacturing process, and level of personnel competency as used for flight hardware.*

- **Flight Model (FM)**: *A flight model is the complete spacecraft to be sent to orbit.*

The system-level tests discussed in this thesis are described in detail in Appendix A.

2.1.2 U.S. Military Standards

The two primary military standards that define government spacecraft test programs are MIL-STD -1540, *Product Verification Requirements for Launch, Upper Stage, and Space Vehicles*, and MIL-STD-340, *Test Requirements for Launch, Upper Stage, and Space Vehicles.*

Spacecraft verification can be accomplished by means of analysis, test, inspection, demonstration, or combination thereof. From MIL-STD-1540, the primary objectives of verification are:

- Verify the design meets performance and interface requirements when exposed to its operational environment,
- Verify the manufacturing process ensures products meet specified design requirements,
- Ensure flight hardware and software are free of workmanship and latent defects and are acceptable for flight,
- Validate equipment functionality and procedures necessary to support ground and flight operations, and
- Predict and confirm vehicle system integrity and performance through all mission phases.

According to MIL-STD-1540, the qualification test program should verify design and manufacturing requirements at the lowest level of assembly possible (component or subsystem). Functionalities that can be affected by integration processes, such as external system interfaces, should be verified at the highest level of assembly (system). The lowest risk programs are typically achieved when qualification testing is conducted on a dedicated QM or when there is a proven flight heritage. From MIL-STD-1540, Table 1 lists numerous potential failure mechanisms along with the qualification tests that could be used to identify them.

The acceptance test program should verify that there are no latent defects or workmanship-precipitated failures in flight hardware that could degrade the mission performance or lifetime. These are less stringent tests than qualification tests. Table 2 lists acceptance tests that could precipitate failure modes, also from MIL-STD-1540.

MIL-STD-340 describes the government requirements for each qualification and acceptance test at the unit, subsystem, and vehicle levels, including details such as levels, durations and margins. Table 3 lists the primary vehicle qualification tests and the probability of them being required, and Table 4 lists the primary acceptance test requirements. However, the test program should be tailored based on spacecraft hardware and software heritage, expected failure modes, and the level of risk acceptable to the customer.

Table 5 identifies other factors that should be considered when designing a test program. Many of these factors, such as similarity to previous qualification articles and product complexity, will be considered in the development of the Rapid AIT test plan, described in Chapter 3.

Table 1. Qualification Tests to Identify Failure Modes [7]

Potential Failure Mechanism	Primary Qualification Tests to Identify Failure Mechanism									
	Functional	Vibration or Acoustic	Shock	Thermal Cycle	Thermal Vacuum	Acceleration	Leakage	Proof and Burst Pressure	EME	Life
Mounting Broken/Loose	x	x	x			x			x	
Broken Part		x	x	x	x					
Shorted Part	x	x			x				x	
Defective Part	x	x		x	x				x	
Defective Board	x	x		x	x				x	
Broken/Shorted/Pinched Wires	x	x		x	x				x	
Defective/Broken Solder	x	x		x	x				x	
Contamination		x	x	x	x					
Leaky Gaskets/Seals/RF					x		x		x	
Incorrect Wiring/Router Design	x	x							x	
Relay/Switch Chatter		x	x						x	
Adjacent Circuit Board Contact		x	x						x	
Premature Wearout		x								x
Electromagnetic Interference									x	
Insufficient Design Margin	x					x		x	x	
Corona Discharge/Arcing					x					
Inadequate Tiedown of Tubing/Wiring		x				x			x	
Inadequate Thermal Design				x	x					
Brittle Material Failure			x							
Inadequate Fatigue Life		x		x						x

Table 2. Acceptance Tests to Precipitate Failure Modes [7]

Potential Failure Mechanism	Primary Acceptance Tests to Precipitate Failure Mechanism									
	Functional	Wear-In	Vibration or Acoustic	Shock	Thermal Cycle	Thermal Vacuum	Leakage	Proof Pressure	Proof Load	EME
Parameter Drift	x		x		x	x				
Electrical Intermittents - Solder Joints - Loose Wires - Connectors			x	x	x	x				x
Latent Defect Parts	x		x	x	x	x				
Parts Shorting			x							
Chafed/Pinched Wires			x							x
Adjacent Circuit Board Contact			x	x						
Parameters Changing Due to Deflections			x		x	x				x
Loose Hardware			x	x						x
Moving Parts Binding		x				x				
Leaky Gaskets/Seals					x	x	x			x
Lubricants Changing Characteristics		x			x	x				
Material Embrittlement				x	x	x				
Outgassing/Contamination			x	x		x				
Degradation of Electrical or Thermal Insulation						x				x
Corona Discharge/Arcing						x				x
Defective Pressure Vessels								x		
Structural Defects									x	
Defective Wiring	x									x
Defective Tubing							x			

Table 3. Vehicle Qualification Tests [7]

Test	Requirement
Inspection[1]	**R**
Functional[1]	**R**
Pressure/Leakage	**R**
EMC	**R**
Shock	**R**
Acoustic or Vibration[2]	**R**
Thermal Cycle[3]	**O**
Thermal Balance[4]	**R**
Thermal Vacuum	**R**
Modal Survey	**R**
R = High Probability of Requirement	
O = Low Probability of Requirement	
1. Required before and after each test as appropriate	
2. Vibration conducted in place of acoustic for compact vehicle	
3. Required if thermal cycle acceptance test conducted	
4. May be combined with thermal vacuum test	

Table 4. Vehicle Acceptance Tests [7]

Test	Requirement
Inspection[1]	**R**
Functional[1]	**R**
Pressure/Leakage	**R**
EMC	**O**
Shock	**O**
Acoustic or Vibration[2]	**R**
Thermal Cycle	**O**
Thermal Vacuum[3]	**R**
Storage	**O**
R = High Probability of being required	
O = Low Probability of being required	
1. Required before and after each test as appropriate	
2. Vibration conducted in place of acoustic for compact vehicle, less than 180kg	
3. Requirements modified if thermal cycle conducted	

Table 5. Test Requirement Considerations [9]

Criticality to mission
Sensitivity to environment
Severity of environment
Knowledge or uncertainty of environment
Similarity to previously qualified articles
Ability to analyze vs. design margins
Maturity of technology
Maturity of production line
Level of assembly vs. simulation
Product complexity
Cost of repair and retest for problems found at higher level of assembly
Use of qualification models for flight-alternative strategies
Benefits of dedicated qualification articles
Prior experience with statistically significant sample of similar products
Training and experience of manufacturing, AIT personnel
Use of automated vs. operator performed manufacturing operations
Manufacturing process controls proven to produce defect-free products of similar designs and complexity

2.1.3 Space Mission Analysis and Design

Used in undergraduate, post-graduate, and continuing education courses, *Space Mission Analysis and Design* (SMAD) is a leading text for space systems design and systems engineering. The text takes the reader through every commonly accepted step of the development process, from mission design to launch operations. This section will describe the guidelines for spacecraft AIT as presented in SMAD to provide a background in the traditionally accepted testing process and timeline.

The S/C AIT process usually lasts at least six months, and in many cases many years [8]. This is primarily due to extensive qualification testing intended to validate the spacecraft design is suitable to meet its mission requirements. Figure 5 depicts the traditional flow for qualification tests, which can take more than a year. There are three commonly accepted ways to qualify a design [8]:

- **Dedicated Qualification Hardware –** *A separate set of qualification components is constructed and tested at qualification levels. This set of qualification components is then assembled into a Qualification Model (QM) of the spacecraft and tested at qualification levels. This hardware is dedicated to qualification testing and does not launch.*

- **Qualify the First Set of Flight Hardware –** *The first set of flight components is tested at qualification levels. These components are then assembled into a spacecraft which is tested at qualification levels. This spacecraft is launched. This is the "proto-flight" concept.*

- **Qualify by Similarity –** *Demonstrate that the components and the environments are identical to previously qualified hardware.*

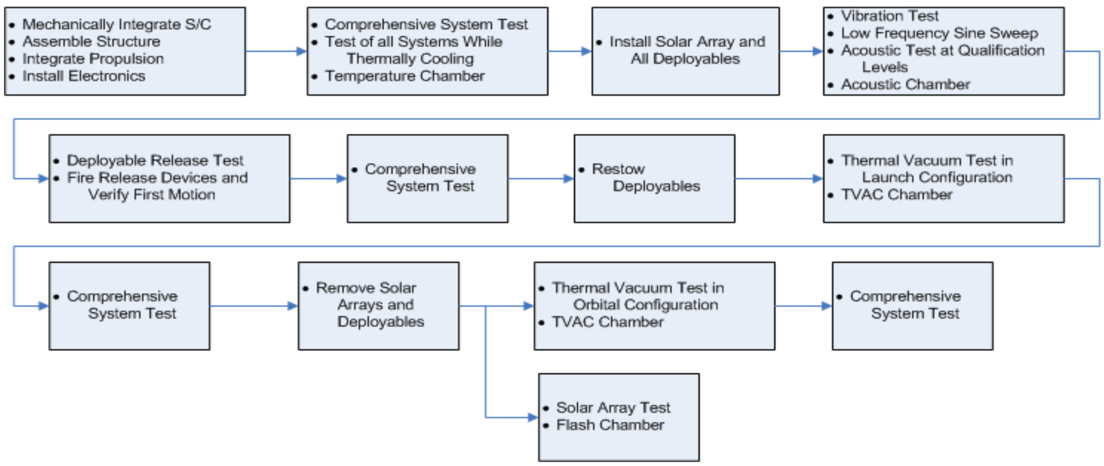

Figure 5. Typical Qualification Test Flow [8]

Because the qualification process can last more than a year, qualifying a spacecraft by similarity would be a desirable choice for ORS. The Type Test Theory (Figure 6) states that if one article passes all qualification tests, an identical article (component, subsystem, system) will also pass. In other words, the qualification test program qualifies a design by which other articles can be built. However, validity of the theory is dependent upon ensuring that all components or systems are built to the same set of engineering data such as drawings, specifications, procedures and processes. If the article has been built to the same specifications as previously qualified hardware, less stringent acceptance tests are used to certify workmanship. The Type Test Theory could be applied to an ORS S/C program to pre-qualify designs, cutting the on-demand timeline significantly.

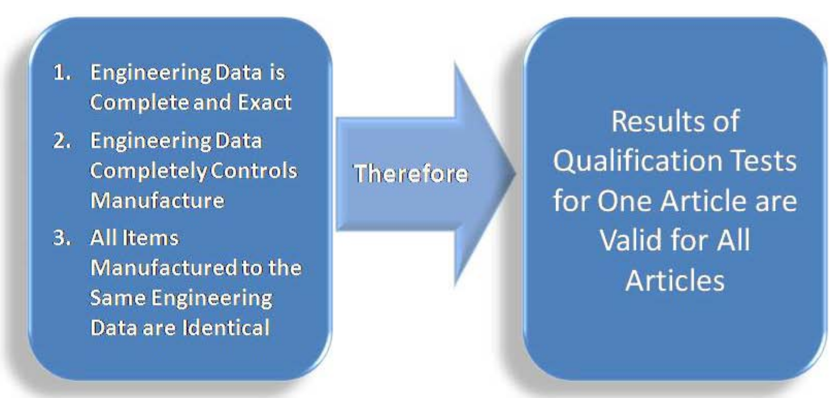

Figure 6. Type Test Theory [8]

2.1.4 Test Thoroughness and On-Orbit Failure Research

Multiple studies have been completed to examine the correlation between test thoroughness (based on MIL-STD-1540) and on-orbit failures. There are many interrelated factors that can affect on-orbit failure statistics, some of which are test thoroughness, system complexity, launch mass, and production sequence. The studies presented in this section use the Environmental Test Thoroughness Index (ETTI) to rank test thoroughness. The ETTI is a qualitative technique to subjectively assign a measure of adequacy to spacecraft test programs based on compliance with MIL-STD-1540 [10]. The ETTI assigns weighting factors for qualification tests, acceptance tests, and level of assembly.

2.1.4.1 Establishing Minimum Test Standards Based on Complexity

Wendler describes the considerations involved in determining environmental test standards as "The four C's": craftsmanship, complexity, cost, and constraints. While all four considerations are important, his study focuses on the correlation between S/C complexity, ground testing and on-orbit failures [11].

Wendler defines complexity of the system by electronic piecepart count, ignoring solar array contribution. A piecepart is defined as electronic parts that come from a line assembly production, like diodes, hybrids, resistors, etc. Using past studies and numerous data points on on-orbit failures, Wendler shows a correlation between on-orbit infant mortality mission degrading failures (MDF) and ETTI rating.

Figure 7 shows the level of ETTI needed to sustain one, two, or three MDFs for a given spacecraft complexity. MDFs are defined as failures which cause reduction in mission duration or availability within the first 120 days from launch. Examples may include a leak in a propulsion valve degrading mission life, or switching to a redundant unit from a primary unit which might degrade mission reliability. It can be seen in Figure 7 that for a spacecraft of lower complexity (≤ 50,000 piece parts) that relatively low test thoroughness could be tolerated. However, a more complex vehicle (≥ 250,000 piece parts) would require full MIL-STD-1540 compliance, which includes full qualification testing, to avoid mission degrading failures. Full compliance can be time consuming and costly; so, some programs implement a shorter test program with added redundancy in the system. Redundancy can increase risk tolerance, therefore decreasing the level of compliance that can be tolerated. Redundancy could be a method of buying down risk for ORS satellites while decreasing test robustness.

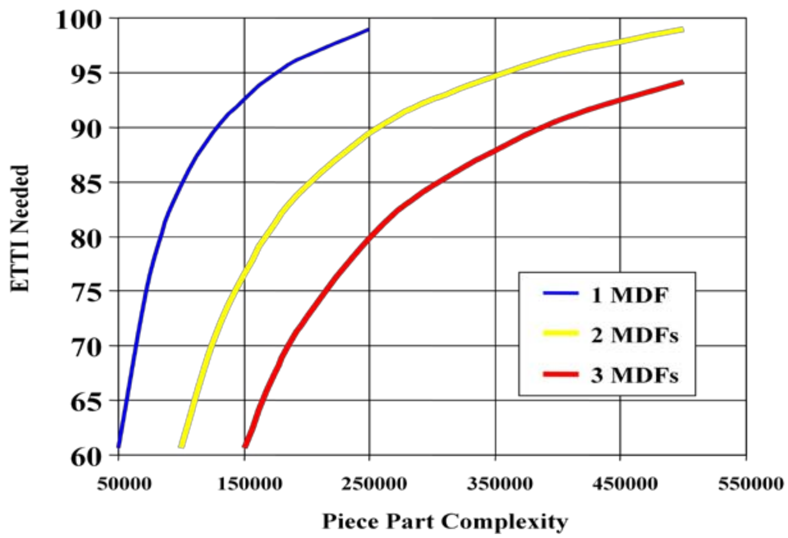

Figure 7. Mission Degrading Failures with Respect to S/C Complexity [11]

Because spacecraft testing can be time consuming and costly, Wendler also investigated ways to optimize the testing based on system complexity. Using complexity to normalize the family of spacecraft investigated, he examines the optimal number of component-level TVAC cycles to precipitate/discover discrepancies. Adequate box level testing is important to decrease the number of failures at the system level where it can cost 10 or more times to remove and fix the problem [11]. It was found that 10 cycles with 85ºC temperature swings is optimal.

Anything greater than 10 cycles will probably not result in fewer discrepancies discovered in system level TVAC, and will needlessly increase cost and time.

The results of Wendler's study show that spacecraft complexity should be a consideration when designing a test program. For a spacecraft of given complexity, the level of compliance to MIL-STD-1540 can indicate the number of expected mission degrading failures on orbit. Less complex spacecraft may be able to tolerate a low threshold for test robustness with few failures, while more complex spacecraft could gain tolerance of low compliance with added redundancy. The complexity of PnPSat-1 and correlated level of test thoroughness will be analyzed for the Rapid AIT test plan development, detailed in Chapter 3. While complexity can be a method of determining minimum test standards for a system, craftsmanship, cost, and constraints should also be taken into consideration. A conclusion can also be made that programs should conduct adequate component- or subsystem-level tests to eliminate many of the discrepancies discovered during system-level test.

2.1.4.2 The Influence of Development and Test on Mission Success

Tosney, Arnheim, and Clark collected data on 454 satellites encompassing all U.S. manufactured satellites launched form Jan 1980 – Nov 1999 for the purposes of correlating test thoroughness, complexity, launch mass, and production sequence with on-orbit mission failures [12]. In this case, the failure statistics include catastrophic or degrading failures within the first 3 years of on-orbit operation. Strong correlation was found between on-orbit failures and ETTI. Figure 8 show an exponential decrease in failures as ETTI rating increases, underscoring the importance of thorough testing. The relationships between failures with respect to launch mass or complexity are also quite interesting. Data suggests that as mass or complexity increase, as do number of failures – with the exception of the lowest mass and complexity categories (Figure 10,

Figure 9). This outlying category is probably due to the experimental nature of most small satellites, where the satellites are one-of-a-kind and in a lower level of development. Experimental satellites also tend to have a lower ETTI than the larger, more complex satellites. Complexity, in this case, is based on 17 weighted, independent parameters such as payload type, number of deployables, and redundancy factor.

The final relationship discovered by Tosney et al. is between failures and number of vehicles produced (sequence number). This is also an exponential relationship, but is even more striking than the ETTI correlation. The R-squared value for the sequence relationship is 0.94, while the ETTI R-squared value is 0.88. This is a strong suggestion that as the production increases the number of on-orbit failures will decrease. This is probably due to lessons learned being incorporated, workmanship errors decreasing, and equipment errors being discovered and fixed.

The results of this study make a powerful argument that test thoroughness can decrease the number of on-orbit failures. However, the most prominent correlation to failures is the production sequence. As the number of satellites produced increases, there tends to be an exponential decrease in the number of on-orbit failures. This analysis could suggest to ORS that confidence in a satellite design and AIT processes can be gained over time.

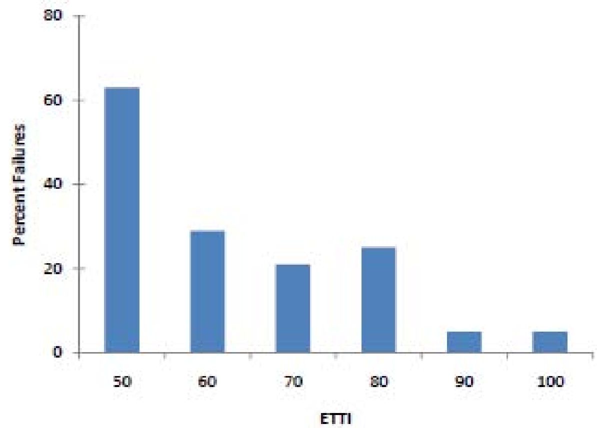

Figure 8. Percentage of Failures vs ETTI [12]

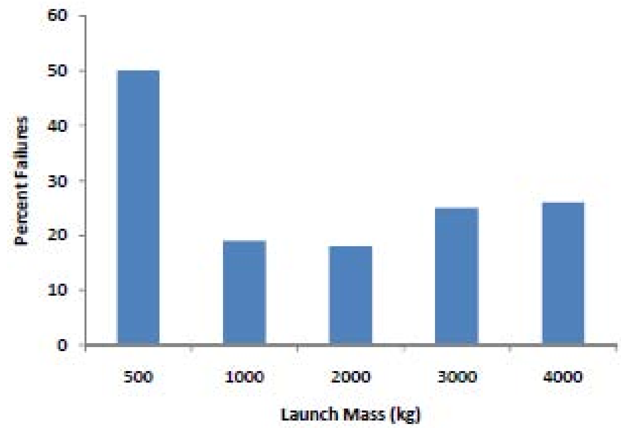

Figure 10. Percentage of Failures vs Launch Mass [12]

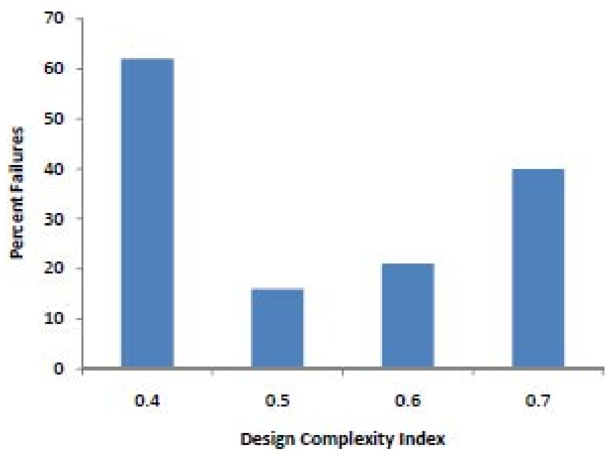

Figure 9. Percentage of Failures vs Complexity [12]

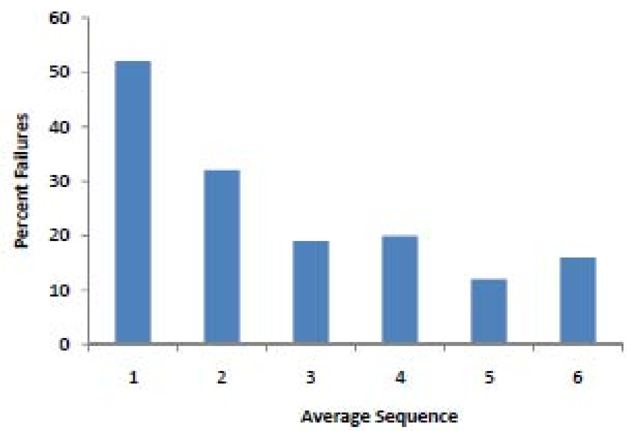

Figure 11. Percentage of Failures vs Vehicle Sequence Number [12]

2.1.5 Spacecraft System-Level AIT Discrepancy Research

Weigel evaluated over 23,000 spacecraft discrepancies (anomaly reports) to characterize the types of anomalies found during system-level testing [13]. The anomaly reports studied are from the development of 224 spacecraft representing at least 20 different programs. The spacecraft evaluated are from different vendors for both commercial and government programs.

The motivation for Weigel's research came from the Lean Aerospace Initiative (LAI), a partnership among U.S. government, MIT, and aerospace businesses. The Lean concept was born out of the International Motor Vehicle Program research project. It is described as a way to “do more with less and less while coming closer and closer to providing customers with exactly what they want” [13]. A key Lean concept is minimizing waste, which includes discrepancies at the system level. The spacecraft system-level AIT discrepancy research presented by Weigel is the first LAI product to solely address the spacecraft sector.

While the product development process of a spacecraft is similar to that of other complex products, there are some key characteristics unique to manufacturing spacecraft [13]:

- A typical lot size for spacecraft is 1. Large lot sizes are considered to be around 6-8. The largest lot size ever produced was 77 spacecraft for the Iridium constellation.
- Spacecraft are assembled primarily by hand, with extensive touch labor. This large human-in-the-loop factor greatly increases the chances that discrepancies will occur during AIT.
- Typical order-to-delivery cycle spans 24-36 months for commercial programs, 24-84+ months for government programs.
- As contrasted with aircraft, spacecraft are operated in a “no-return” environment. This results in risk-averse customers that usually dictate extensive testing and verification.

The reports were studied to determine during which system-level test activity the anomalies were discovered (Figure 12). It was found that the vast majority of anomalies were detected during ambient activities – nearly 2/3 of all anomalies reported. The remaining reports occurred during environmental tests: Shake (including acoustic, vibration, acceleration, and shock), TVAC and thermal cycle. Of the environmental tests, TVAC testing was the largest contributor to anomaly detection. Ambient activities include any activity taking place in an ambient environment not included in the other categories, initial and final functional tests, and any functional tests not associated with the environmental exposure. TVAC activities include setup and post-environment activities, TVAC test itself, and immediate post-environment functional tests.

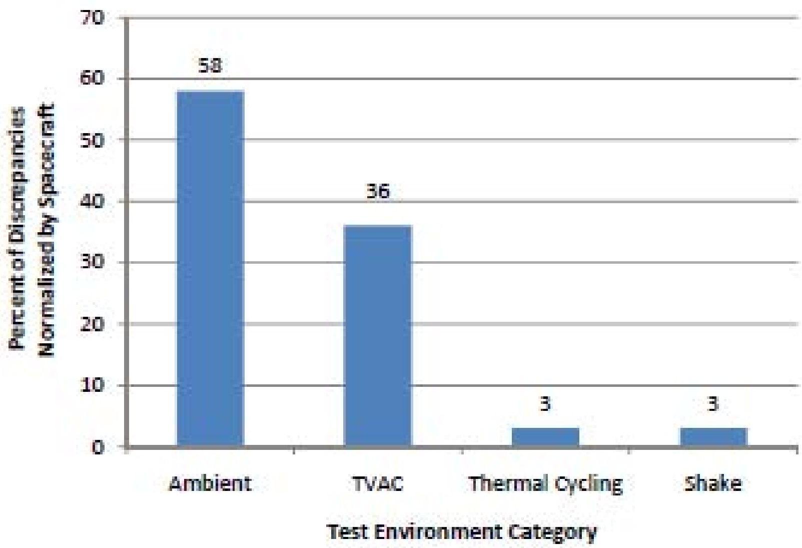

Figure 12. Anomaly Distribution Among Test Categories [13]

Some interesting correlations were found in these test categories. First, as anomalies found during ambient activities increased, those found during TVAC testing decreased. This may indicate that some of the anomalies reported during TVAC testing could have been discovered in ambient activities with more time or attention to detail. Secondly, as anomalies discovered in the TVAC testing activities increased, the number of discrepancies with "Use As Is" corrective action increased. This may be due to an operator's misunderstanding of the proper operation at temperature extremes, resulting in erroneous reports.

The anomaly reports were also categorized into subsystems (Figure 13), root causes (Figure 14), and corrective actions (Figure 15). The primary subsystem reported against was Equipment with 29%. The items in this category are non-flight, ground support equipment (GSE). Furthermore, the data in Figure 16 indicates that significant subsystem problems are found at the system-level testing. Only 35% of all anomalies discovered during system-level test are problems at the system level. For the purposes of this research, the following definitions are used:

- **Subsystem –** *Electrical Power and Distribution Subsystem (EPDS), Guidance Navigation and Control (GNC), Propulsion, Payload, Structures and Mechanisms (SMS), Data Management and Telemetry, Tracking and Command (DMS/TTC), Thermal, Wiring and Cabling (Harness).*

- **Spacecraft –** *Discrepancies that cannot be traced to a particular subsystem.*

- **Equipment –** *Test equipment or ground support equipment of any type.*

The Operator Error, Design, and Equipment categories accounted for the largest percentage of root causes (27%, 25% and 17% respectively). Half of the failures were caused by non-spacecraft items, such as Operator Error and Equipment.

The primary corrective action amongst the entire data set was the No Action Required disposition (24%), with the Employee/Operator, Drawing/Spec, Process/Procedure and Software/Equipment accounting for much of the rest. Only 1% of corrective actions are categorized as Supplier-Related.

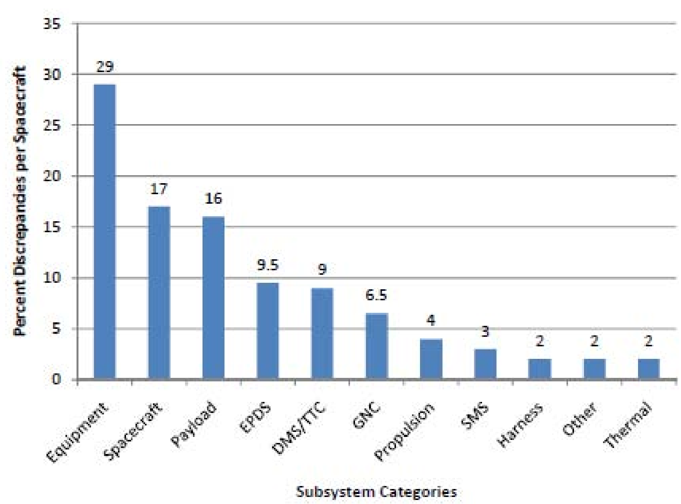

Figure 13. Distribution of Discrepancies Subsystem Written Against [13]

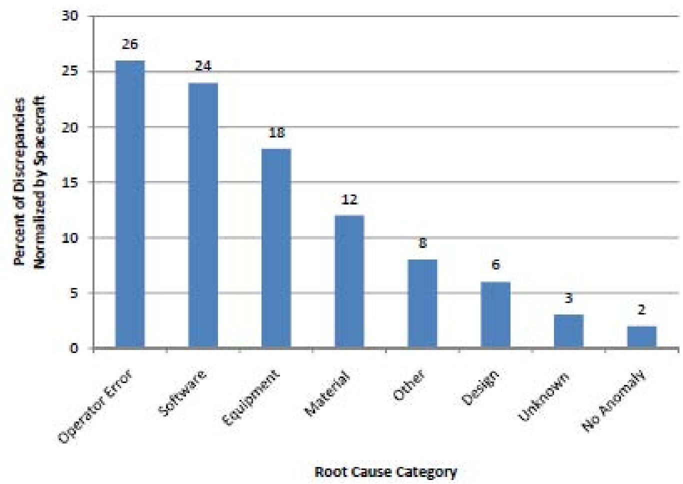

Figure 14. Distribution of Discrepancies in Root Cause Categories [13]

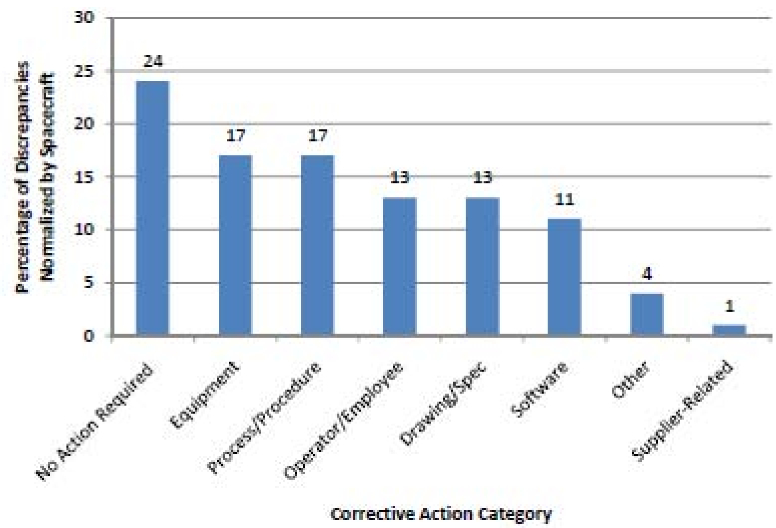

Figure 15. Distribution of Discrepancies in Corrective Action Categories [13]

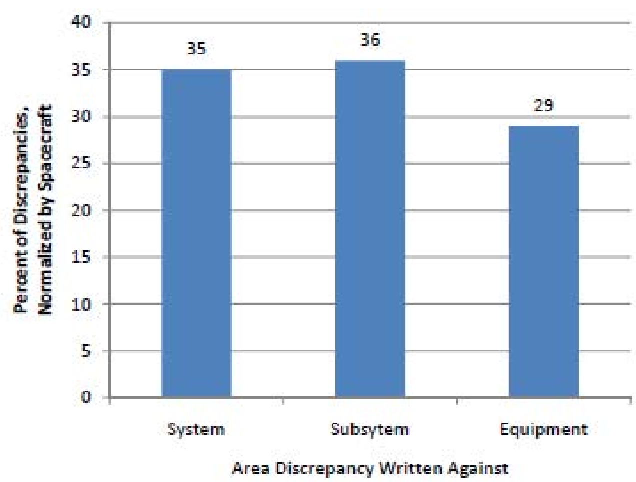

Figure 16. Distribution of Discrepancies by Area Written Against [13]

With Weigel's research, aimed at better understanding spacecraft anomalies to apply the Lean concept of minimizing waste, one can draw many interesting conclusions. A summary of the highest contributor to each category studied is shown below (Table 6). Because the majority of problems found during system level test were actually recorded against subsystems and equipment rather than the system itself, it may be beneficial to conduct more testing at the subsystem-level. It appears to be especially valuable to exercise subsystems with extensive ambient testing (burn-in) and the TVAC test, which could expose many discrepancies that increase cost and schedule during system-level integration. Also, because operator error and equipment account for half of the system-level problems, it would be prudent to employ training programs and validation procedures for equipment.

Table 6. Summary of Highest Contributors in Each Category [13]

Category	Primary Contributor	Percentage
Activity in which anomaly is found	Ambient TVAC	58% 36%
Subsystem written against	Test Equipment	29%
Disposition	Use As Is	39%
Root Cause	Operator Error Design	27% 25%
Corrective Action	No Action	23%

2.2 Rapid Satellite Production Examples

There are multiple examples in industry of programs that have updated their AIT processes with the intent of decreasing the time involved in qualifying a spacecraft. The RADARSAT program is one example of a traditional satellite program that has updated its processes between the first and second models with lessons learned and technology advancements [14]. There are more relevant examples of rapid production of satellites, like Globalstar, which reduced the timeline for flight models to one week [19]. This section provides a discussion of rapid AIT processes employed in the spacecraft production industry. Lessons learned from these programs can be incorporated into the design of a test program for an urgent-need satellite.

2.2.1 RADARSAT-1 and RADARSAT-2

RADARSAT-1, the first Canadian earth-observing satellite, was launched in 1995 and continues to provide Synthetic Aperture RADAR (SAR) imagery to government and commercial users. The 5-year design life has long past, so RADARSAT-2 was developed to ensure a continued SAR data supply. RADARSAT-2 launched 14 December 2007 with many enhancements over the RADARSAT-1 design.

The RADARSAT-2 design has evolved from the original, as did its AIT program [14, 15]. During the RADARSAT-1 AIT program, Bus Electronic Ground Support Equipment (EGSE) and Payload EGSE were developed by the bus and payload developers, respectively. The two EGSE systems were not easily integrated with one another which lead to the first of the AIT program changes: utilizing the Mission Operations ground system at both the payload and system levels. This first change allows the payload specialists, AIT team, and Mission Operators to be familiar with the in-orbit operating system early on. Using a single ground system while decoupling payload tests from spacecraft tests decreased complexity and time of the AIT phase.

The RADARSAT-2 program took a different approach to some of the system-level tests. By using enhanced TVAC technologies and thermal modeling techniques, thermal engineers were able to correlate the thermal model and TVAC Data to within 5% of the predicted thermal response. Deployment test methodology was also improved for RADARSAT-2. The deployment mechanisms were subjected to extensive qualification testing at the unit level (including TVAC) and were therefore only acceptance-tested at the subsystem and system levels with pre- and post-vibration deployments. Components that were previously qualified were acceptance-tested at both the unit-level and at the system-level.

While the AIT program did evolve between RADARSAT-1 and -2, some aspects remained the same. By utilizing the existing test facilities and ground segment, much complexity was removed. Not only was the equipment proven, but the technicians, engineers, and operators have experience with them. Experience can be invaluable to solving a problem quickly and correctly.

By building on the experience of the RADARSAT-1 AIT program, RADARSAT-2 was able to enhance their AIT program with updated technology and methodology. Requiring extensive qualification testing at low levels of assembly enabled RADARSAT-2 to reduce the number and complexity of system-level tests without reducing confidence in the spacecraft design and construction. Also, by taking advantage of proven equipment and experienced personnel the number of discrepancies caused by operator error or faulty equipment can be reduced.

2.2.2 ORBCOMM

Orbital Sciences Corporation's ORBCOMM program cites market pressures for their need to depart from traditional satellite production processes [16]. The ORBCOMM constellation provides world-wide, low cost, reliable, two-way communications. The space segment consists of 36 small (< 50 kg, 42 in diameter, 6 in pre-deployment height) communications satellites in Low Earth Orbit (LEO) [17]. ORBCOMM plans to launch 18 second generation satellites with improved capability and Automated Identification System (AIS) starting as early as 2010 [18]. Figure 17 shows a stack of 8 ORBCOMM satellites during integration to the Pegasus launch vehicle.

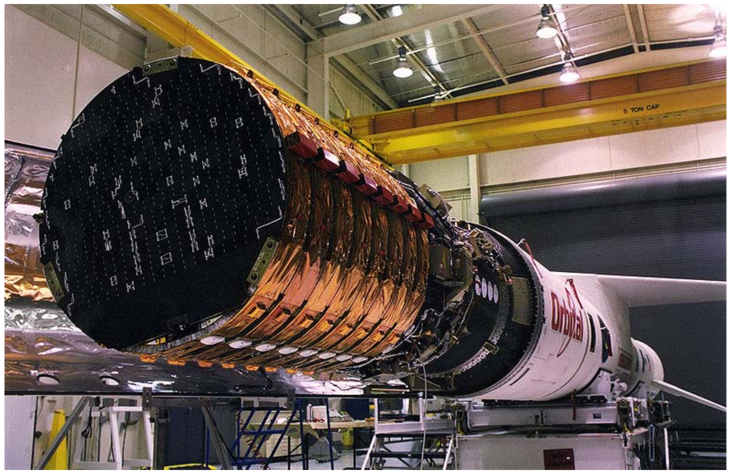

Figure 17. ORBCOMM Satellites in Pegasus Launch Vehicle Integration [19]

Schedule demands on the ORBCOMM program require tasks to be accomplished in parallel. Figure 18 depicts multiple ORBCOMM satellites being manufactured in parallel. Another way they reduced timeline was by testing only basic functionality of components in environmental tests rather than performance. Also, as the number of satellites produced increases and confidence is established in AIT processes, some tests are removed from the AIT flow. For example, only the QM went through shock and acoustic testing, and only the first 4 FM went through TVAC testing. Table 7 lists all of the test activities for the QM and FM 3-36.

Figure 18. Manufacture of Multiple ORBCOMM Satellites in Parallel [19]

Table 7. ORBCOMM Test Requirements [16]

	Spacecraft System and Environmental Tests									
	Static Loads	Modal Tap/Sine	Magnetic Calibration	Random Vibe	Shock	Thermal Balance	Thermal Vacuum	Thermal Cycle	EMI	Functional
QM	x		x	x	x	x	x		x	x
FM 3-4	x	x	x	x			x		x	x
FM 5	x	x	x	x			x	x	x	x
FM 6	x	x	x	x			x	x	x	x
FM 7	x	x	x	x				x	x	x
FM 8	x	x	x	x				x	x	x
FM 9	x	x	x	x					x	x
FM 10	x	x	x	x					x	x
FM 11	x		x	x					x	x
FM 12	x		x	x					x	x
FM 13-36	x		x	x					x	x

ORBCOMM also employed on-line production processes and automated functional testing to further improve the AIT flow. All procedures and test scripts are stored on a central server to allow easy and immediate access to the latest revisions and redlines, and unreleased versions are not accessible on the AIT floor. The operator will use this same server to check off completed steps and enter test data to be cataloged. This system has access controls and permissions, and in some critical steps requires passwords from Quality Assurance Engineers (QA) to proceed. Anomalies and spacecraft status are also tracked in the on-line system. Controlled test scripts are used to ensure tests are repeatable and consistent.

The ORBCOMM program was able to cut their AIT timeline by altering the typically-accepted testing standards, performing tasks in parallel, utilizing on-line technologies for configuration control, and enforcing strict AIT discipline. Many of the measures developed in the ORBCOMM AIT program could be applied to ORS satellite programs to reduce their AIT timeline.

2.2.3 Globalstar

Globalstar is a constellation of LEO satellites, used for phone and low-speed data communications. The first of 52 first-generation satellites (~550 kg each) was launched in 1998, and concluded in 2000. Bridging the gap in service life between the first- and second-generation satellites, eight spare first-generation spacecraft were launched in 2007. The second-generation constellation is set to begin launch in 2010. [20]

To reach a production rate of 1 satellite per week, the Globalstar program departed from traditional AIT processes [21, 22]. Globalstar was successful in launching 64 LEO S/C (500 kg) in one and a half years. Similar to the ORBCOMM approach, a QM went through a full complement of qualification tests while FM's went through an acceptance test sequence to validate the final assembly. It can be seen in Figure 19 that the acceptance test sequence consisted of fewer tests than the qualification sequence. TVAC and thermal balance was reduced to a thermal cycle test, and multiple vibration tests were reduced to only a random vibration test. Also similar to the ORBCOMM program, FM test requirements were decreased as confidence in the design and assembly process was gained.

The Globalstar program employed a signature-based approach to determining the likeness of a FM to the QM by comparing the FM test data (signature) to the QM test data (signature). Otherwise, additional testing would need to be conducted to establish qualification. For example, a 5% threshold between the FM and QM natural frequencies was required to call an FM identical [22]. This threshold will be used when comparing the Rapid AIT Demonstration data to the baseline data.

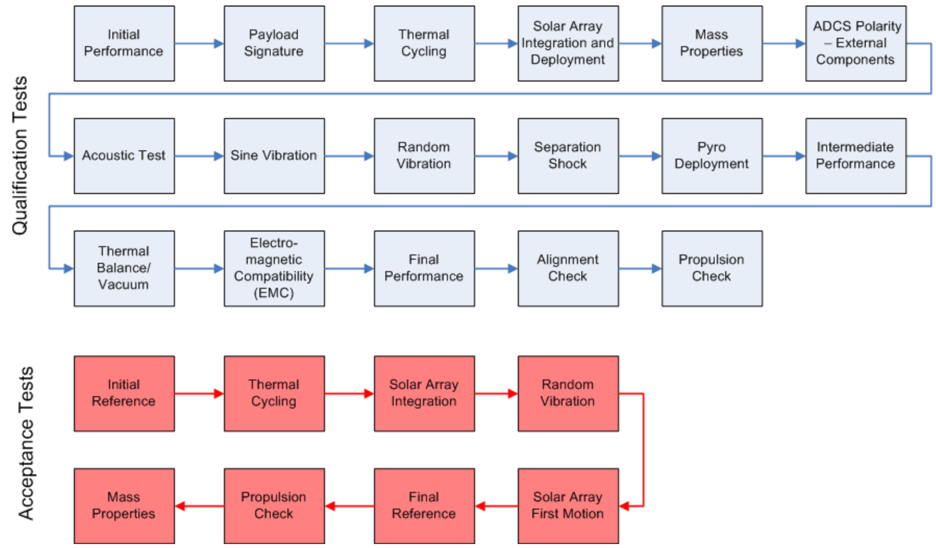

Figure 19. Globalstar Qualification and Acceptance Tests [22]

Because of Globalstar's unique facility and GSE design, if an anomaly was found within a specific article, it could easily be removed from the production line to allow troubleshooting without disrupting the production flow. Each satellite was built on a fixed stand moving between "islands" – the stations in the production line. Each island performed a specific operation, keeping personnel focused on one task and limiting the movement of GSE. Also to decrease timeline, the facility operated two vibration tables simultaneously. Vibration tests were limited to one axis, utilizing only 1/3 the number of accelerometers used in qualification testing. The Globalstar program was able to achieve an intensive production rate without impacting the final product performance [22]. Their AIT methods can provide valuable lessons to be considered in the Rapid AIT Demonstration. While the facility cannot be altered for this demonstration, the idea of assigning specific duties to personnel, limiting GSE movement, and reducing vibration tests will be incorporated into the Rapid AIT Demonstration plan.

2.2.4 Iridium

Lockheed Martin's Iridium constellation of satellites provides world-wide satellite voice and data communications. The 66 operational satellites (Figure 20) create the space-based network over which communications are relayed to anywhere on the globe. Along with the satellite constellation, the ground network and Iridium subscriber products are primary system components.

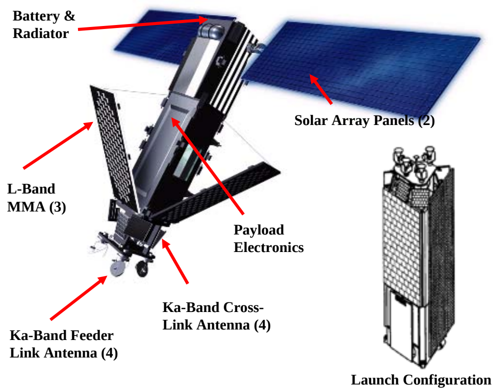

Figure 20. Iridium Satellite Configuration [23]

By departing from traditional AIT processes, the Iridium program achieved low cost (<$13M per S/C) and rapid production (22 days per S/C) of satellites [23]. Between May 1997 and May 1998, 72 Iridium satellites were launched successfully. The most recent launch was in 2002. As of 2005, there were 66 operational satellites in the constellation and 12 spares in a storage orbit.

Lockheed Martin Missiles and Space President, Mr. Michael Henshaw, stated that standardized interfaces will be the enabler for spacecraft buses to become off the shelf [24]. In a speech given at the Air Force Association's Partnerships in Space Symposium in 1998, Mr. Henshaw stated the following:

> We made some money on Iridium buses. We are going to build 140 by the time it's all over. We do every one of them just alike, every time. Do you know that Iridium is only "thermal vac-ed" on the first bird and the next 150 won't see the thermal-vac chamber? I had a lot of sleepless nights over that issue – having come from a world where for 30 years if you changed a screw, you went back from thermal-vac. Yet the world is going to higher rates and industry is going to higher rates because of the uniformity from one unit to the next. You will be able to get out of expensive cycles of test.

The Iridium program has some differences from ORS Tier-2 because their mission is quite different. Iridium is a constellation of duplicate satellites with no change in configuration between each. Also, the production was continuous, rather than on demand. However, due to the similar goal of moving the space industry toward rapid deployment of low cost satellites, some valuable lessons can be learned from the Iridium program.

Some of the lessons learned from the Iridium program are:

- Design the S/C to facilitate repair and upgrades
- Use standard design tools (including simulation and modeling)
- Automate design and development tools (including software coding)
- Automate testing (scripts, tools, and procedures)
- Use pathfinder to proof S/C handling, facilities, mechanical GSE (MGSE), and to train personnel
- Utilize on-orbit reprogrammable flight software (FSW)
- Decrease test time by using automation, built-in-tests, self-test and reports, and properly placed test interfaces
- Eliminate launch site testing – use only aliveness checks or a self check
- Eliminate some tests for identical designs.

In 2007, the Iridium LLC announced “Iridium NEXT”, an upgrade to the existing constellation [25]. This new system will provide greater bandwidth and backward compatibility for current users. Iridium NEXT will be more than a personal communications network though. The company envisions NEXT providing many more services to the aerospace community – global LEO imaging, satellite data relaying, and hosting 50 kg secondary payloads as an enabler to ORS [25, 26].

2.2.5 TacSat-2

TacSat-2, considered the first operationally responsive space satellite, was launched 16 December, 2006 and ceased operations 21 December, 2007. The Advanced Concept Technology Demonstration was aimed at implementing rapid spacecraft production, launch, and on-orbit checkout. Yee describes the methods employed on the TacSat-2 program to achieve reduced AIT duration from the traditional two to three years to a more responsive 15 months [27].

Yee states that there are multiple areas within the satellite development process that can be adjusted for shorter duration. The first of these is in the preparation for system-level AIT. The TacSat-2 program utilized functional engineering models of the components/payloads, which Yee claims can eliminate ninety percent of the electrical interface issues that might arise during flight unit integration. The use of engineering models also helped in developing quality assembly and test procedures. The engineering models were tested on a “FlatSat” testbed, such that functional testing or troubleshooting could occur in parallel to integration activities on the S/C (See Figure 21).

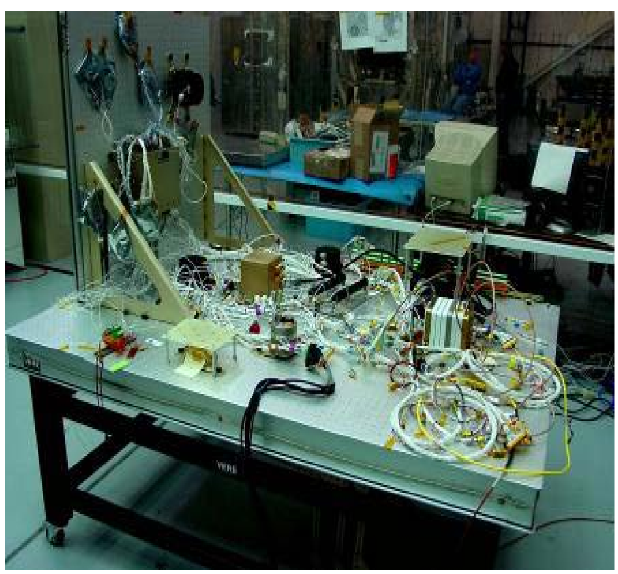

Figure 21. TacSat-2 FlatSat Testbed

Also during AIT preparation, Yee stated that the assembly and test procedures should be written and validated. The level of detail in the assembly and test procedures should be tailored to the particular level of expertise of the personnel that will use them. Only the critical elements of a procedure should be included in the procedure checklist, rather than creating a complete repository of knowledge that may be cumbersome and time-consuming to follow. Consequently, a strong training program will need to be implemented to pass on the knowledge required to adequately perform the AIT activities.

Another area in the satellite development process that can be streamlined is test documentation, including assembly and test procedures. The TacSat-2 program implemented a self-documenting test system which recorded all commands and telemetry to/from the spacecraft. The test scripts created log files, automatically documenting every script-generated response (commands, error messages) and operator inputs (commands, error descriptions, prompt responses). When any unexpected condition was encountered, the operator was prompted to input an explanation and continue or abort for troubleshooting.

Through the use of the test scripts with limit checking and error reporting, the operator did not need to have expertise with every component/payload on the spacecraft. The script would alert the operator if an unexpected condition occurred and it would then be up to the operator and quality assurance representative to determine if the condition was a test glitch or component malfunction. Troubleshooting periods were also self-documenting through the command and telemetry recordings and log files.

TacSat-2 is considered the first operationally responsive space satellite and can provide many lessons to ORS in the areas of AIT preparation, documentation, and test automation. Yee identifies using engineering models, a troubleshooting testbed, self-documenting test procedures, and automated test scripts as enablers to reducing the AIT timeline from 3 years to 15 months.

2.3 Applicability of Lessons Learned to ORS

2.3.1 Limitations of Lessons Learned

There are no perfect analogies between existing spacecraft programs and the ORS Tier-2 concept. In the ORBCOMM, Globalstar, and Iridium examples, the flight models were all identical to the qualification models. In the ORS concept, the S/C will be of identical architecture, but not configuration based on mission requirements. This may pose a limitation on the use of the Type Test Theory (qualification by similarity). Further research to identify how closely a flight model must match a qualification model in configuration for the Type Test Theory to apply may be warranted.

The ORS concept also allows for a variable production rate, or operations tempo, based on the on-demand requirements of the JFC. Variable operations tempo may provide some logistical challenges for ORS. The level of in-stock inventory, inventory functionality checks, and personnel readiness are all considerations in determining the Chileworks concept of operations. To maintain readiness for a six-day call up scenario, where only two days is dedicated to satellite AIT, the required components must be available and functioning, and the personnel must be proficient in the AIT process. ORS should consider continual training exercises in Rapid AIT, which will provide hands-on experience for operators and extensive pre-Rapid AIT system-level testing. The variability of S/C configuration and operations tempo causes some unique concerns for ORS that should be addressed in future studies.

2.3.2 *Applicable Lessons Learned*

Despite some aspects of Rapid AIT that are unique to ORS, there are industry concepts that can be utilized for a responsive satellite. Some of the lessons from the provided industry examples that could be considered in developing the Chileworks rapid AIT facility, operations, and spacecraft are:

- Develop modular spacecraft design,
- Standardize interfaces,
- Eliminate/reduce tests as confidence in AIT process is built,
- Test only functionality, rather than performance, in system-level tests,
- Determine a threshold for likeness between Qualification and Flight Models,
- Personnel should perform one operation to maintain proficiency,
- Design facility to reduce hazardous and timely spacecraft movement operations, GSE movement, and cut time between operations,
- Utilize on-line systems to control and catalog procedures, drawings, and test data,
- Automate functional tests to ensure repeatability and consistency,
- Employ experienced personnel for both AIT and operations,
- Determine minimum testing standards based on complexity of spacecraft and risk posture,
- Develop testing standards for components, subsystems, and ground support equipment to reduce failures exposed during system level test,
- Reduce complexity of S/C design as much as possible, and utilize redundancy when appropriate,
- Execute continual Rapid AIT operations to refine procedures, maintain proficiency, and detect discrepancies early,
- Maintain and calibrate test equipment regularly, and
- Implement a personnel training program.

These lessons will be considered in developing the test plan for the Rapid AIT Demonstration.

The application of these lessons will be detailed in Chapter 3.

3. Rapid AIT Demonstration Description

The Rapid AIT Demonstration is a series of tests exploring the premise that current spacecraft system-level test requirements can be reduced or modified for ORS satellites. This demonstration was conducted at Kirtland AFB, NM from April-December 2009. This chapter first describes the objectives and format of the demonstration. Then, the test plan and rationale are provided. Finally, the PnPSat-1 test article is described in detail.

3.1 Rapid AIT Demonstration Plan

This section will first introduce the Rapid AIT Demonstration, including the trial format, team members, and responsibilities. Also included is a detailed description of the test plan development utilizing research presented in Chapter 2. Finally, the personnel, facility, and equipment requirements are defined.

3.1.1 Demonstration Introduction

Six Rapid AIT trials were completed between April-December 2009. The baseline testing, conducted at AFRL previous to the demonstration, is referred to as Trial 0. The objectives of each of the trials can be seen in Table 8.

There are two separate groups of personnel that performed the Rapid AIT activities and are referred to as Team A and Team B. Team A consists of personnel intimately familiar with PnPSat-1. Team B is spacecraft technologists that are familiar with AIT but not with PnPSat-1 specifically. The roles of the teams are listed in Table 8 and the team members are listed in Table 9. Team B will be trained during Trial 1 and will perform AIT on Trial 2. An objective of personnel changes is to investigate how dependent the Rapid AIT success and timeline are on number of personnel and mix of skill set. Multiple S/C configuration changes may provide insight into how similar a flight model must be to a qualification model to be qualified by similarity.

Each trial consists of four stages: Planning, Rapid AIT, Validation Tests, and Analyze Data, as shown in Figure 22. During the planning stage, the procedures, configuration files, and drawings are updated and reviewed. The Rapid AIT stage is executed by the responsible team with oversight from the opposite team. This stage is video recorded and timed. Discussion regarding the Rapid AIT duration will be presented in Chapter 4. The validation tests are a series of more traditional spacecraft AIT activities such as TVAC and 3-axis vibration tests. These tests are conducted to further validate that there were no failures precipitated by or missed during the Rapid AIT activities. Finally, the data should be analyzed to document any problems/failures and make changes for further trials.

Table 8. Rapid AIT Demonstration Trial Descriptions

Trial	Objective	Description	Roles
0	Baseline	Baseline data (pre-demo) will be considered QM data set. Pre-demo runs will validate draft procedures.	Team A Conduct
1	Test Initial Rapid AIT Flow	The experts will conduct the Rapid AIT process with the new personnel learning. One Team B member provides QA.	Team A Conduct Team B Follow
2	Timed Rapid AIT	The experts will conduct the Rapid AIT process with the new personnel learning. One Team B member provides QA.	Team A Conduct Team B Follow
3	Test Rapid AIT Robustness with New Personnel	The new personnel will conduct the Rapid AIT process with the experts monitoring. One expert provides QA.	Team B Conduct Team A Follow
4	Change Configuration	New S/C configuration using existing PnP components	Team B Conduct Team A Follow
5	Timed Assembly	Media Event – timed assembly and functional tests only	Team A & B Conduct
6	Change Configuration	New S/C configuration using existing and new PnP components	Team A & B Conduct

Table 9. Rapid AIT Demonstration Team Description

Team	Role	Members
Program Management/Systems Engineering	Management, program direction, technical objectives	Howerton Moretti
Principal Investigator	Test plan development, record lessons learned, analyze results	Baghal
Team A	Experienced PnPSat personnel—Trials 1 and 2 lead and post-trial validation lead	DiPalma Stottlemyer Stroka Ortiz
Team B	Personnel inexperienced with PnPSat – Trials 3-4 lead.	Robinson Lewis Anderson Baghal

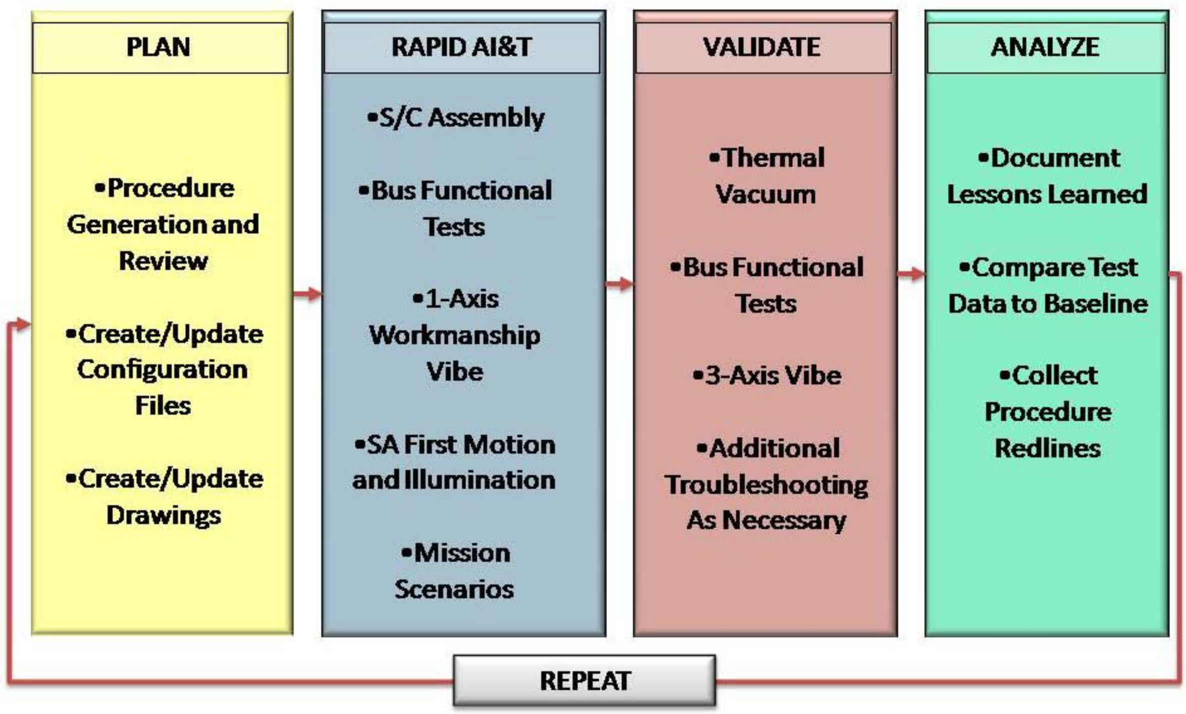

Figure 22. Rapid AIT Demonstration Trial Process

3.1.2 Rapid AIT Plan Development

Using previous research, industry-accepted guidelines, lessons learned, expert knowledge, and standard industry practices, a Rapid AIT test plan was developed by the Principal Investigator (PI) and various team members. Using MIL-STD-1540 as the basis from which the test flow originated, tests were modified, reordered, or removed in an attempt to meet the ORS Tier-2 Rapid AIT timeline. This section will describe the changes to traditional AIT practices and rationale.

The fundamental assumptions of this research are based on the ORS Tier-2 baseline concept of operations as follows:

- Fully qualified components remain in stock at the Chileworks facility,
- Multiple S/C bus designs have been fully qualified (qualification models), and
- When the JFC identifies an urgent need, a flight model will be built and tested in Rapid AIT from the qualified components and bus designs.

3.1.2.1 Type Test Theory

The Type Test Theory is a method of qualifying spacecraft based on similarity to a qualification model (Section 0). Following the Type Test Theory, the Rapid AIT Demonstration test suite is focused on workmanship tests rather than design tests because the designs are assumed to be qualified by similarity. Typically, workmanship tests are thought of as a function of assembly (bolts torqued, connectors mated). In the case of PnPSat-1 (and future ORS systems), selecting components and FSW modules to meet desired mission (gathering correct parts kit) is also a function of workmanship. Therefore, workmanship tests will also consist of mission scenarios.

The basis of the Type Test Theory states that the QM and FM must be identical in design. The QM test data can then be used as a baseline for comparison to the FM data and will determine the suitability of the FM for flight. Baseline test data was gathered prior to the demonstration began in March 2009 (Trial 0), and will be considered the QM data used for comparison in future trials. While not all trials will be identical in configuration to the baseline, the configurations will be similar due to a lack of component/structure inventory. Because the bus structure carries the structural load and provides the heat transfer path in the spacecraft [5], a common bus structure or a selection of common structures could be a first step in assuring similarity in both structural and thermal responses. In addition to utilizing common structures, well-tuned analytical models may be an option for predicting changes in structural and thermal properties for a change in component configuration. A suggested future research topic is to study how close to identical the S/C must be for the Type Test Theory to apply.

3.1.2.2 Discrepancy Categorization Research

The selection of Rapid AIT activities can be supported by the research conducted at MIT in 2004 (Section 2.1.5). In a study of 224 S/C and over 23,000 discrepancies, less than 1/3 of S/C discrepancies were discovered during environmental testing, while over 2/3 of S/C discrepancies were reported during ambient activities. Also, only 35% of all discrepancies were categorized as system-level discrepancies. Subsystem and equipment discrepancies made up 36% and 29%, respectively. The high discrepancy discovery rate in ambient activities coupled with the realization that most discrepancies are attributed to subsystems and equipment suggests that if sufficient ambient and environmental testing, especially TVAC [13], is conducted at the component or subsystem level prior to Rapid AIT the majority of failures could be exposed prior to Rapid AIT. Therefore, ORS should consider long periods of ambient and environmental testing on components/subsystems prior to system-level integration to expose discrepancies.

3.1.2.3 Using System Complexity to Determine Test Standards

Using Wendler's definition of system complexity as number of IEEE piece parts (Section 2.1.4.1), a minimum test standard can be determined. Images of multiple electronics boards from both the PnPSat-1 avionics and the components were studied. The number of piece parts on each board was counted, and the average number of parts per square inch of electronics board was calculated. The total electronic board area was compiled based on the PnPSat-1 receive and inspection information. This information allowed a system complexity estimate of 23,000 piece parts. This is less than the lowest category (50,000 parts) in Wendler's data set. Wendler's research suggests that for a risk of one infant mortality mission degrading failure, the PnPSat-1testing would need to be 60% compliant to MIL-STD-1540. The more important conclusion, however, is that the correlation between test thoroughness, complexity, and on-orbit failures is not linear. PnPSat-1 is smaller and less complex than ORS may envision for Tier-2 S/C. As such, it would be prudent to conduct an investigation into the affect of complexity on the Rapid AIT Demonstration results.

3.1.2.4 Lessons Learned

Many satellite programs provide lessons that can guide the development of the Rapid AIT test plan. RADARSAT is an example of a traditional spacecraft program that decreased system level test on the second model due to confidence built in their first S/C. Acceptance based on confidence is the same course of action that the ORBCOMM, Iridium, and Globalstar programs took in manufacturing their successful constellations. The ORBCOMM program eliminated Shock, Thermal Balance, TVAC, and Thermal Cycle for Flight Models 9-36 (Section

2.2.2). The Iridium program only conducted TVAC testing on their first S/C (Section 2.2.4). The Globalstar program eliminated TVAC and Sine Sweep vibration testing on many of their FM's (Section 2.2.3). The Globalstar program gained confidence in their flight models by comparing the acceptance test data from the FM to the QM data, referred to as a signature-based approach. The signature-based approach will be used in the Rapid AIT Demonstration, where the baseline data collected at AFRL acts as the QM data and each trial provides new FM data. Based on all three of these examples, TVAC will not be included in the Rapid AIT test sequence.

3.1.2.5 Expert Survey

The author conducted a survey of industry experts at the Responsive Space 7 Conference (RS7) in April 2009. Participants were asked to assign a risk level associated with eliminating selected system level tests. The responses indicated that with proper qualification testing on a QM and at the component and subsystem level, only a moderate risk would be assumed by eliminating any of the tests. Figure 23 shows both the average level of risk assigned by all participants (mean), as well as the most reported answer (mode). By examining the mode it may be clearer how the majority of participants assign risk, rather than examining the average which can be skewed by one answer. Eliminating vibration tests was assigned the greatest risk (4 on a scale of 1-5). The participants noted that vibration testing can uncover many workmanship errors that could be induced by the heightened sense of urgency associated with Rapid AIT and should not be abandoned completely. For this reason, a 1-axis vibration test is included in the test plan. See Appendix C for the full surveys and Appendix D for the survey results.

3.1.2.6 Requirements Verification Matrix

Based on the PnPSat-1 AIT Manager's expert knowledge, a set of requirements was compiled to determine how the spacecraft functionality should be verified. The requirements verification matrix can be found in Appendix B. Each requirement was categorized by verification method: Inspection, Design, Analysis, or Test. Testable requirements were then categorized into component level tests (performance) on the QM (design tests) or in Rapid AIT (workmanship tests). Many requirements can be tested during Rapid AIT as they are exercised during mission scenarios. Also, tests that can be accomplished in a relatively short period of time, but garner a significant payoff in mission assurance, are included in the test plan.

Using the requirements verification matrix, previous research, lessons learned from previous AIT programs, and the RS7 survey results, a list of tests to be completed for Rapid AIT was compiled. The list of Rapid AIT tests, along with the rationale for each, is shown in Table 10. Next, a test flow was created to maximize the process efficiency and minimize the time required. Typically, the environmental test flow should follow the expected flight sequence (vibration, shock, and TVAC) [5]. Though TVAC and shock tests are not completed during Rapid AIT, the test flow will draw on this philosophy. For example, solar array first motion, deployment, and illumination tests will follow vibration testing. These tests will be followed by mission scenarios.

Though it may seem counterintuitive to insert a bus functional test in the middle of S/C assembly, the rationale is actually to save time – if a dysfunctional component is discovered while the S/C is still in a "flatsat" configuration, it can be replaced or fixed without the added steps of disassembling the S/C external components and structure. Of course, functional tests should be completed after all major activities, like assembly and vibration tests, to ensure there have been no failures induced by the activities. External thermal control blankets and radiator tapes are installed in parallel to mission scenarios, saving more time than doing those activities serially. Throughout the test flow, AIT technicians will be encouraged to accomplish tasks in parallel, if safety of the S/C and personnel permits.

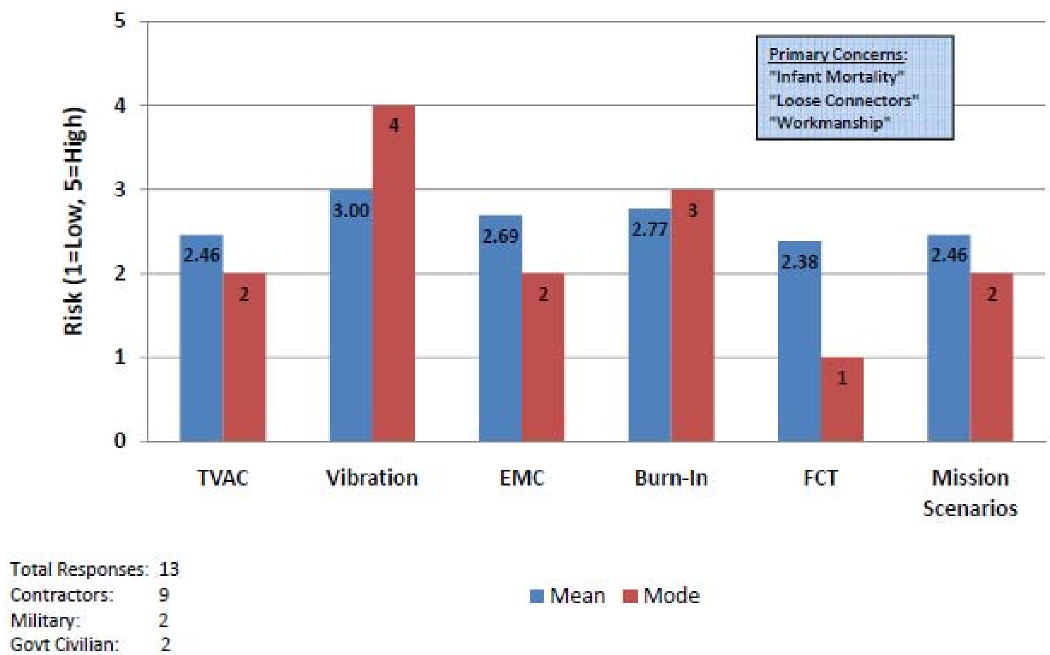

Figure 23. Risk Associated with Eliminating System Level Tests

Table 10. Rapid AIT Activity Summary

Test	Rationale
Bus Functional Test	Short duration test, can be conducted at various levels of integration to verify components are installed correctly and are functioning. This can be a time saving step as a fault would be found during this short duration test before investing time into a more expensive test. Does not verify performance criteria as this was accomplished in unit qualification testing. Includes a polarity check of ADCS components.
Payload Functional Test / Calibrations	Verifies payload functionality – critical to mission success.
Mass Properties	Verifies all parts installed, ensures launch vehicle requirement met, short duration
1-Axis Workmanship Vibration Test - Lateral Axis	Checking for workmanship errors only. All components are qualified, and similar spacecraft passed qualification tests - therefore design is qualified.
Solar Array Deployment / Illumination	Verifies mechanical and electrical interfaces to spacecraft – critical to spacecraft survival.
Mission Scenarios	Ensures all FSW modules for mission profile loaded and functional.
Factory Compatibility Test (FCT)	Verifies spacecraft communication with ground system – critical to mission success.

* Acceptance minus 6dB is starting level for vibration testing per AFRL/ORS Memorandum of Agreement. If higher levels are required to validate workmanship, levels will be coordinated between AFRL and ORS.

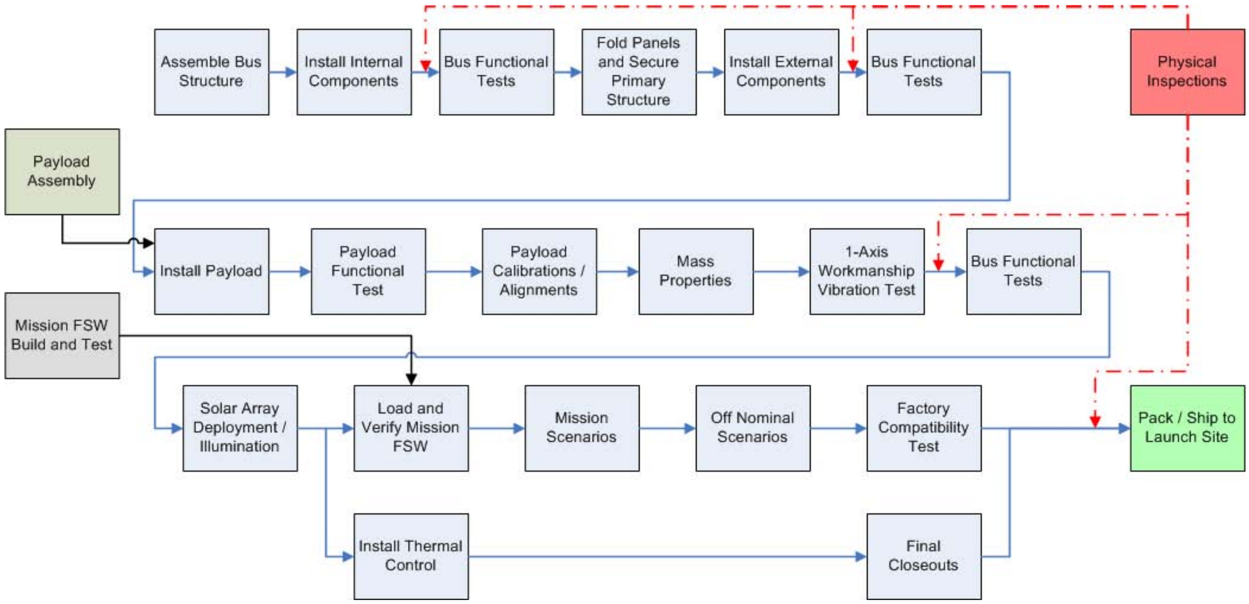

Figure 24. Rapid AIT Flow

3.1.3 Rapid AIT Test Descriptions

This section describes some of the tests to be performed in the Rapid AIT test sequence. The full list can be found in Table 10. Some of the tests listed will not be performed because of the limitations of the test article or available equipment. Section 3.2 provides a description of the PnPSat-1 test article.

3.1.3.1 Bus Functional Test

The bus functional test, as described in Table 10, is utilized to show component functionality during various phases of the Rapid AIT flow. This test is not designed to test performance of components, rather the basic functionality. It will be run as the spacecraft is assembled – one time after internal component installation and one time after external component installation – to verify the components coming off the shelf are not defective. Bus functional tests are relatively quick tests, and can save time by catching faulty components early in the assembly process. If faulty components are found, they can be removed, moved to a troubleshooting area, and replaced with another without disrupting the Rapid AIT flow. Bus functional tests are also run after vibration testing to ensure all components remain functional.

3.1.3.2 Payload Build and Test

The payload build and test sequence is not covered in this demonstration. Upon decision of mission design, a separate flow to build up a payload (whether from component state or as a whole is yet undefined) would occur concurrently with spacecraft assembly. The payload would then be integrated to the S/C and functionality verified.

3.1.3.3 Mass Properties

The weight and center of gravity (CG) will be measured during mass properties. A hanging scale on the lifting crane is used to measure S/C weight. To measure CG, load cells were placed at three locations on a table/stand. The S/C was lowered onto the load cells, and the measurements were taken at each location. Measurements were taken as the S/C was rotated one complete cycle (13 measurements). The values are averaged to determine the measured CG.

The load cells used to take the CG data were only available for Trials 4 and 6. Because the configurations for these trials were different from the baseline, this data will be compared to the analytical structural models. The analysis of this data is presented in Chapter 4.

3.1.3.4 1-Axis Workmanship Vibration Test

The purpose of the 1-Axis vibration test is to validate assembly workmanship. The first two vibrational modes can also be shown by mounting the S/C to the vibration stand such the both the X & Y axes are excited. This was done to collect the most information possible in the shortest test time. The X/Y axis orientation is shown in Figure 25. Pre- and Post-random vibe sine sweeps were conducted. Minimal accelerometers were used, and the locations were recorded for repeatability in all trials. Three accelerometers were placed at the approximate center of gravity height to sense bus rigid body modes; three accelerometers were placed on +Z panel to sense rigid body modes and the +Z panel drumming mode; and three accelerometers were placed on +Y panel to sense rigid body modes and the +Y panel drumming mode. Table 11 lists the accelerometer locations. The analysis of this data is presented in Chapter 4.

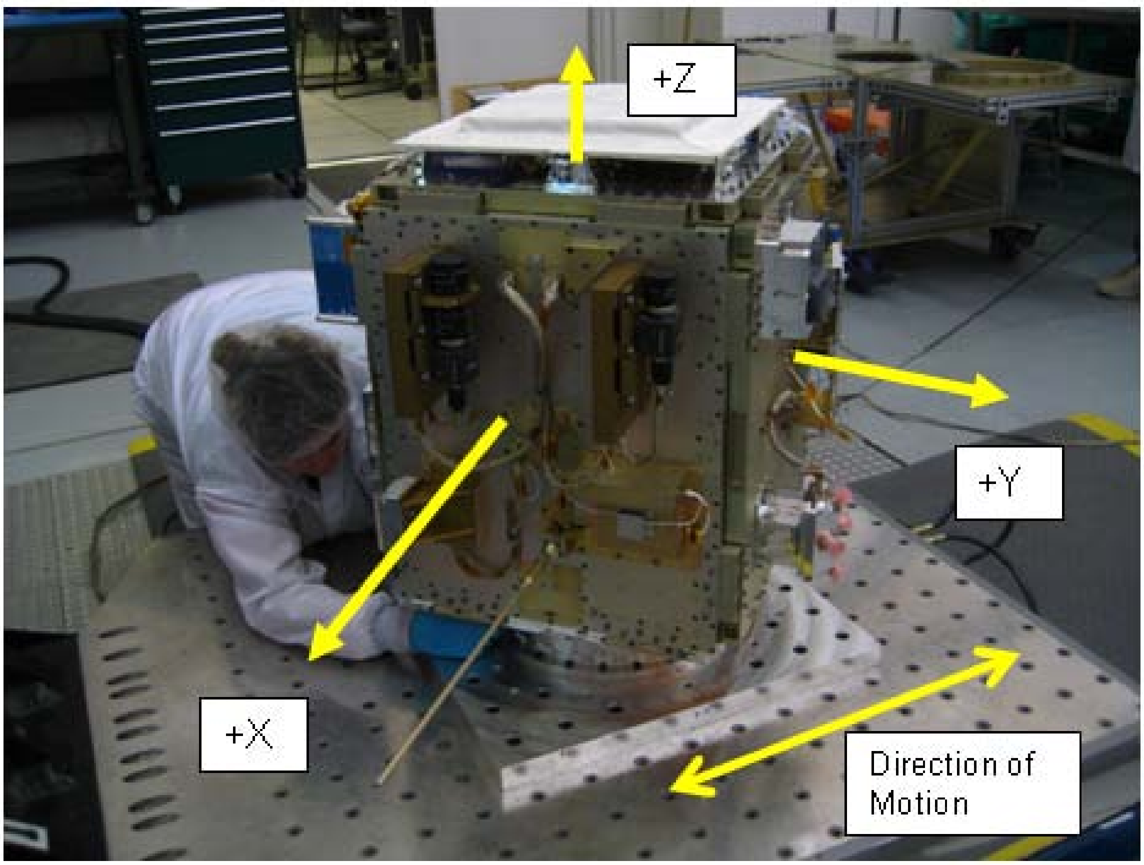

Figure 25. 1-Axis Workmanship Vibration Test Orientation (45 deg off center)

Table 11. Vibration Test Accelerometer Locations

Location	Axis			System Test	Trial 1 Rapid	Trial 1 Validation	Trial 2 Rapid	Trial 3 Rapid	Trial 3 Validation	Trial 4 Rapid	Trial 4 Validation
				003, 004, 005, 006, 008, 009	013, 014	015-020	022, 023	025, 026, 027	030-036	042, 043	045-051
	X	Y	Z								
Fixture	•	•	•	1	1	1	1	1	1	1	1
Fixture	•	•	•	2	2	2	2	2	2	2	2
On +Z Panel, +Y Side, S-Band	•			3							
On +Z Panel, +Y Side, S-Band		•		4							
On +Z Panel, +Y Side, S-Band			•	5							
On +Y Panel, -X Edge, CSS	•			6	6	6 **	6	6	6	6	6
On +Y Panel, -X Edge, CSS		•		7	7	7**	7	7	7	7	7
On +Y Panel, -X Edge, CSS			•	8	8	8**	8	8	8	8	8
On +Z, -X Side, SAC	•			9	9	9	9	9	9	9	9
On +Z, -X Side, SAC		•		10	10	10	10	10	10	10	10
On +Z, -X Side, SAC			•	11	11	11	11	11	11	11	11
On Array, +Z Hinge	•			12		23			12		12
On Array, +Z Hinge		•		13		24			13		13
On Array, +Z Hinge			•	14		25			14		14
On +Y Panel Center	•			17	17	17	17	17	17	17	17
On +Y Panel Center		•		18	18	18	18	18	18	18	18
On +Y Panel Center			•	19	19	19	19	19	19	19	19
On -Y Panel, +X Edge	•			20		20			20		20
On -Y Panel, +X Edge		•		21		21			21		21
On -Y Panel, +X Edge			•	22		22			22		22
On Array Inner Panel Center	•			23							
On Array Inner Panel Center		•		24							
On Array Inner Panel Center			•	25							

** Indicates an instrumentation error in the data

3.1.3.5 Solar Array First Motion/Deployment

The Solar Array First Motion/Deployment test is included in the Rapid AIT flow to test the mechanical assembly of the solar array to the spacecraft bus. The illumination test checks the electrical connection between the array and the Electronic Power System (EPS). Generally, illumination should be a fairly quick test since the array is already deployed. However, the PnPSat-1 solar array is not designed to be deployed on the ground. So, for PnPSat-1 Rapid AIT, the first motion test will be validated with the array mounted to the spacecraft, and then will be removed for deployment (walk-out) and illumination. Removing the solar array is not desirable because it takes considerably longer than an array which can be deployed while installed on the S/C.

3.1.3.6 Mission Scenario Tests

Mission scenarios is a simulation of the expected on orbit operation of the S/C. They do not test all of the components, but do engage all ASIMs. The mission scenarios check the Mission Flight Software (FSW) rather than component functionality, further validating the rationale for multiple simple bus functional tests as described above. A limited set of critical off-nominal/fault management cases are tested in the mission scenario. Any additional off-nominal cases should be validated in mission FSW build and test, occurring concurrently with SC mission design and assembly. Mission FSW build and test will not be accomplished during this demonstration due to limited component and FSW module inventory.

3.1.3.7 Factory Compatibility Test

The factory compatibility test (FCT) is an end-to-end communications verification. The FCT was not completed during the demonstration due to unavailability of proper test equipment. However, the demonstration is designed to simulate as much of the flight command and telemetry path as possible with both UHF and S-Band radios via the communications portion of the bus functional test. Only the ground antenna and pointing system will not be exercised. Because of security constraints, the S-Band radio will be operated in the bypass mode (no encryption) during the Rapid AIT. It will be verified in the encrypted mode during validation testing.

3.1.4 Validation Test Flow

The purpose of the validation tests conducted at the conclusion of the Rapid AIT phase are to uncover if any discrepancies were missed or precipitated by the Rapid AIT phase. Table 12 provides a summary of the tests included in the validation series, and Figure 26 depicts the test flow. This section will give a brief description of some of the tests.

Table 12. Validation Testing Summary

Test	Details
Bus Functional	Same as Rapid AIT (Table 10)
Vibration Test	3-Axis Vibration Test - ESPA acceptance level minus 6dB*
Mission Scenarios	12 orbits including off-nominal orbits
Thermal Vacuum	Hot/Cold Balance (25°C / 10°C), 1 Cycle (30°C / 0°C)
RF Emissions	In-air Radiated Emissions

*Acceptance minus 6dB is starting level for vibration testing per AFRL/ORS Memorandum of Agreement. If higher levels are required to validate workmanship, levels will be coordinated between AFRL and ORS.

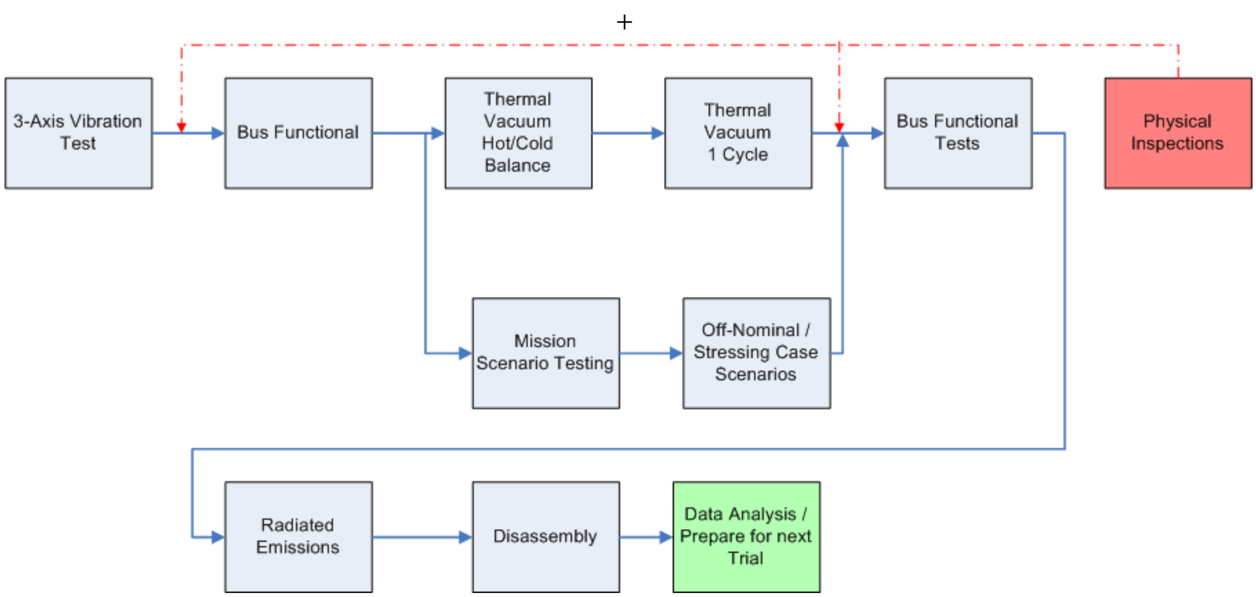

Figure 26. Rapid AIT Validation Test Flow

3.1.4.1 3-Axis Vibration Test

The full 3-axis vibration test is conducted during the validation test series to verify the primary vibrational modes in all three axes. Pre- and post-random vibe sine sweeps are conducted. For this vibration test, additional accelerometers were placed on the solar array restraint panel and bus structure. Table 11 shows the accelerometer locations. The analysis of the 3-axis vibration data is presented in Chapter 4.

3.1.4.2 Thermal Balance/TVAC

The thermal balance and TVAC tests will verify the S/C thermal properties at steady state conditions and temperature extremes. Thermal balance consists of a hot and cold balance at 25°C and 10°C, respectively. The following TVAC test will include one temperature cycle from 30°C to 0°C. Mission scenarios are executed throughout the TVAC test.

External thermocouples were mounted for Trial 1. Figure 27 shows that the external thermocouples and internal panel temperature sensors matched within 1°C, so only internal panel temperatures were used for the remaining tests. The comparison of this data to the baseline tests and analytical model is presented in Chapter 4.

3.1.4.3 Radiated Emissions Test

The radiated emissions test is used to verify proper S/C function in conjunction with the expected radiation from subsystems or components. The radiated emissions test was only completed during Trial 2 validation. It was determined that because of the background noise and unavailability of an anechoic chamber it would be too difficult to find small anomalies. Major anomalies should be found in the radio functional tests, which are part of the bus functional test.

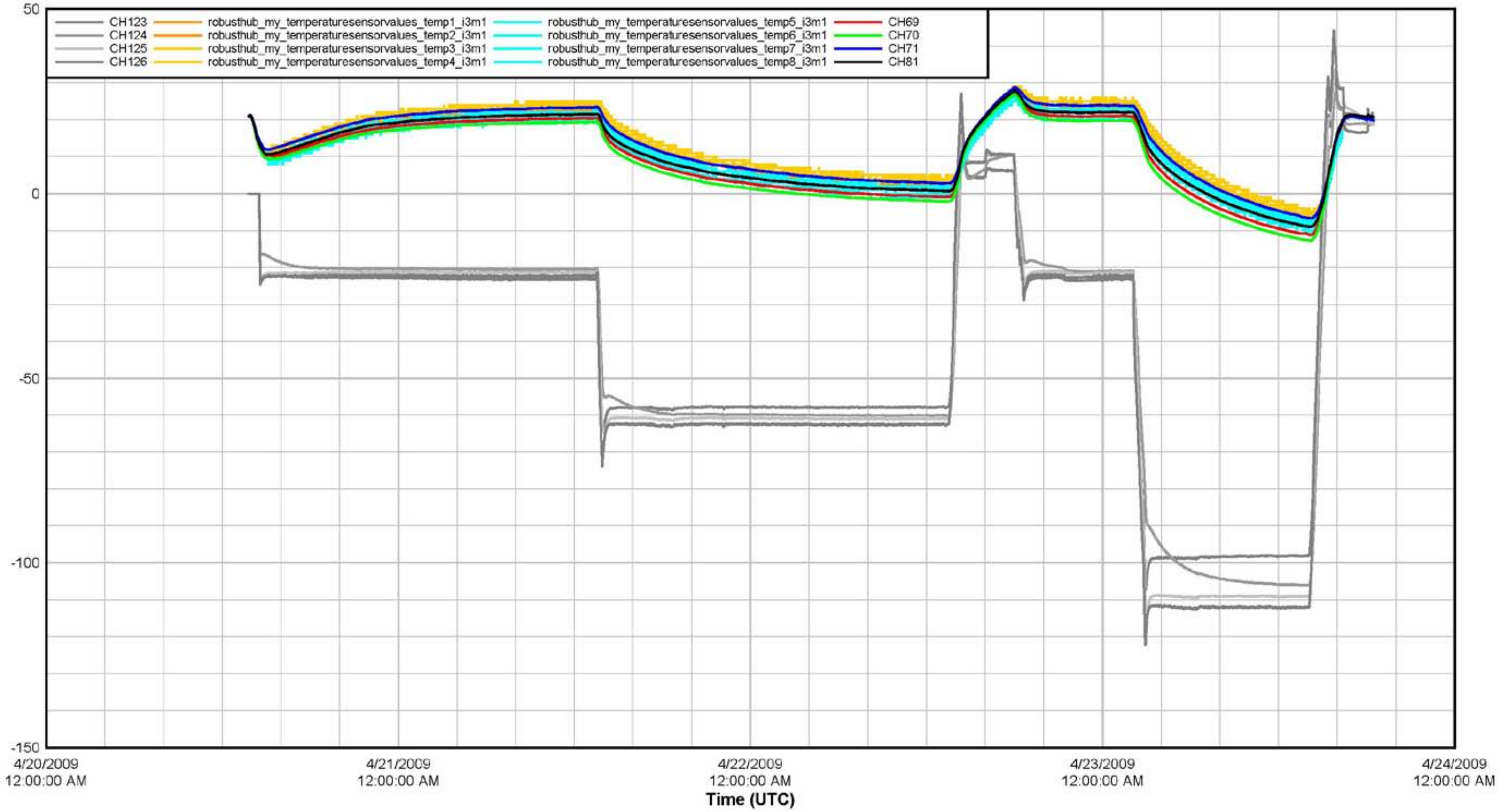

Figure 27. Comparison of External Thermocouples and Internal Panel Temperatures (Deg C)

3.1.5 Facility Requirements

The Aerospace Engineering Facility (AEF) housed the Rapid AIT Demonstration. A 10,000-class clean tent, equipped with S/C integration stand, shelves, tool kits, work benches, and clean room attire was used. The facility also houses a vibration table and thermal vacuum chamber. Figure 28 depicts the facility layout and Figure 29-Figure 31 are images of the primary support equipment.

3.1.6 Personnel Requirements

The personnel executing the Rapid AIT Demonstration are broken into two teams. Both teams consist of 3 people each: one lead engineer, one or two assembly technicians and one test conductor. One person from the opposite team will provide QA during each trial. This requires full time support from members of both teams during each trial.

During the validation test flow, other personnel may be required. The thermal vacuum test is planned for four days and is a 24-hour test. At least two personnel must accompany the S/C during the entire test and must be familiar with executing the Mission Scenario test scripts.

Both the vibration table and thermal vacuum chamber require operators provided by the AEF Staff. The number of operators is left to the discretion of the AEF.

3.1.7 Ground Support Equipment Requirements

The following ground support equipment is required to carry out the tests in the Rapid AIT flow as well as validation testing are listed in Table 13 for completeness. The Electrical Ground Support Equipment (EGSE) is shown in Figure 32.

Table 13. Ground Support Equipment

Ground Support Equipment	
TT&C	S-Band Ground Radio
	S-Band Hat Couplers
	PRC – 117 Radio
	UHF Hat Coupler
	Fiber Optic Cabling
	KI-17
	Direct Connect ASIM
	Direct Connect Serial Connection
	RIMS Command & Telemetry Workstation
	Long Haul Computer
	Short Haul Computer
Power	Solar Array Simulator
	UPS
Diagnostics	Satellite Design Tool
	Digital Volt Meter
	Diagnostic Harness
Mechanical	Integration Stand
	Crane and Lifting Straps
	10-100 Epoxy
	30"lb Torque Screwdriver (2)
	Miscellaneous Hand Tools
	Fastener Lubrication

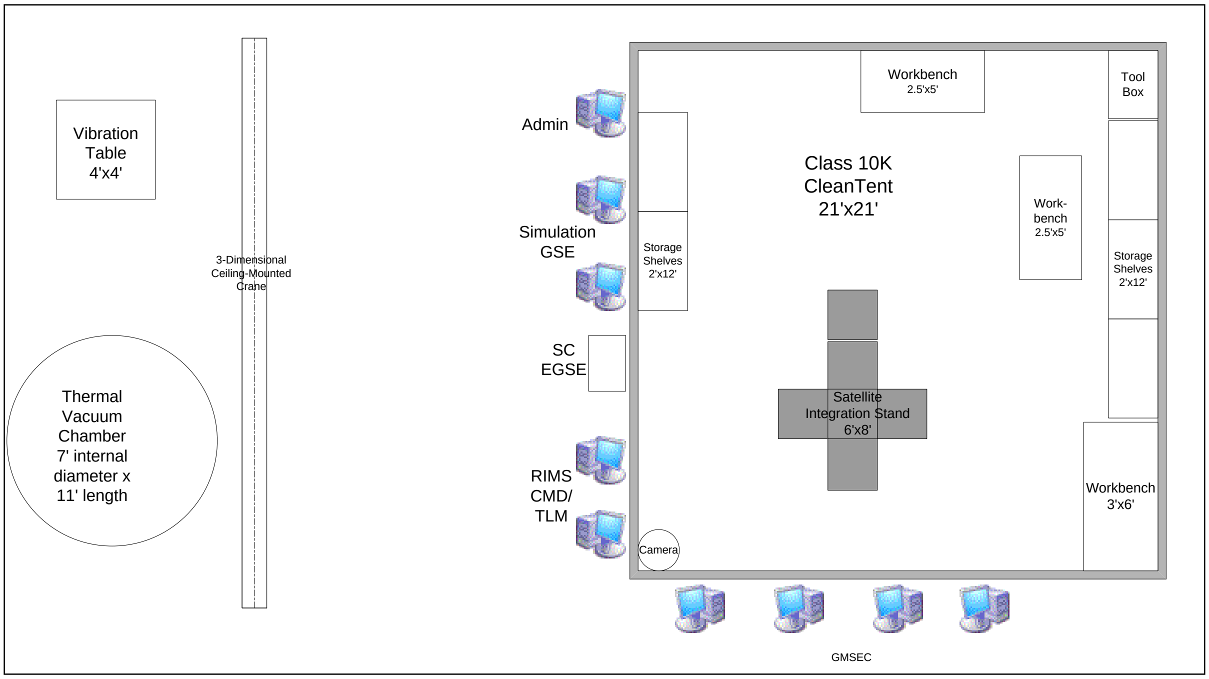

Figure 28. AEF Facility Layout


Figure 29. AEF Thermal Vacuum Chamber

Figure 30. AEF Vibration Table

Figure 31. AEF Clean Tent

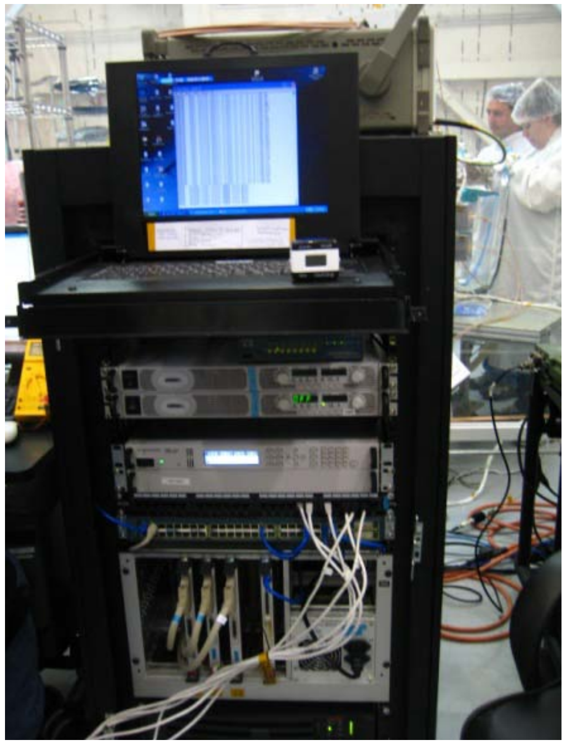
Figure 32. PnPSat-1 EGSE

3.2 PnPSat-1

In 2007, AFRL/RV began development on PnPSat-1, the first full spacecraft utilizing SPA architecture. However, it was decided that the cost of making PnPSat-1 flight worthy outweighed the benefits of launching it. PnPSat-1 is now a testbed for AFRL/RV technology development and ORS exercises. PnPSat-1 is on loan from AFRL as the test article for the Rapid AIT Demonstration.

3.2.1 Structure

The PnPSat-1 structure is constructed of six modular panels with standard PnP mechanical and electrical interfaces. The panels are equipped with locking hinge joints to allow quick assembly and easy interior access. The PnP mechanical interface is a 5.0 x 5.0 cm grid mounting pattern, across both internal and external surfaces. The structural description is summarized in Table 14 . The mass of the structure includes the enclosed electronic infrastructure.

The electronics infrastructure is recessed within the clamshell-style panels, as shown in Figure 33 and Figure 34, to increase footprint area and volume for components. The electronic infrastructure inside each panel provides power and data to endpoints, or “outlets,” on the exterior surfaces of the panel. There are also power and data connections between each panel to ensure a complete satellite power and data network. Components with PnP-standard electrical interfaces can be connected to any endpoint on the spacecraft. Figure 35 is an image of the TacSat-2 interior and Figure 36 is an image of the PnPSat-1 interior. It is can be seen by comparing these two images that the PnPSat-1 panel-enclosed electronics increases the available internal volume and decreases complexity in assembly.

The S/C coordinate system’s origin at the center of the interface of the Motorized Light Band (MLB) separation system and the launch vehicle adapter (Z=0) and the geometric center of the launch vehicle interface (X=0, Y=0).

Figure 37 shows the PnPSat-1 coordinate system. This reference frame will be used to describe the component location for each trial. For example, the top deck panel is referred to as the +Z panel, and the bottom deck (launch vehicle adapter) panel is referred to as the –Z panel.

Table 14. PnPSat-1 Structure Description

External Dimensions	51 x 51 x 61.2 cm
Number of Panels	6
Total Mass	41.6kg

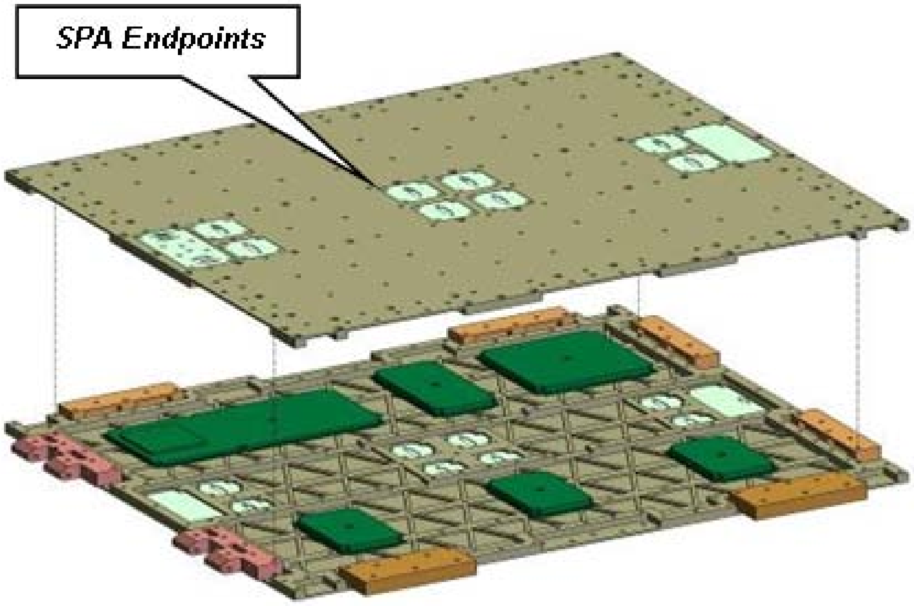

Figure 33. PnPSat-1 Clamshell Panel Illustration [28]

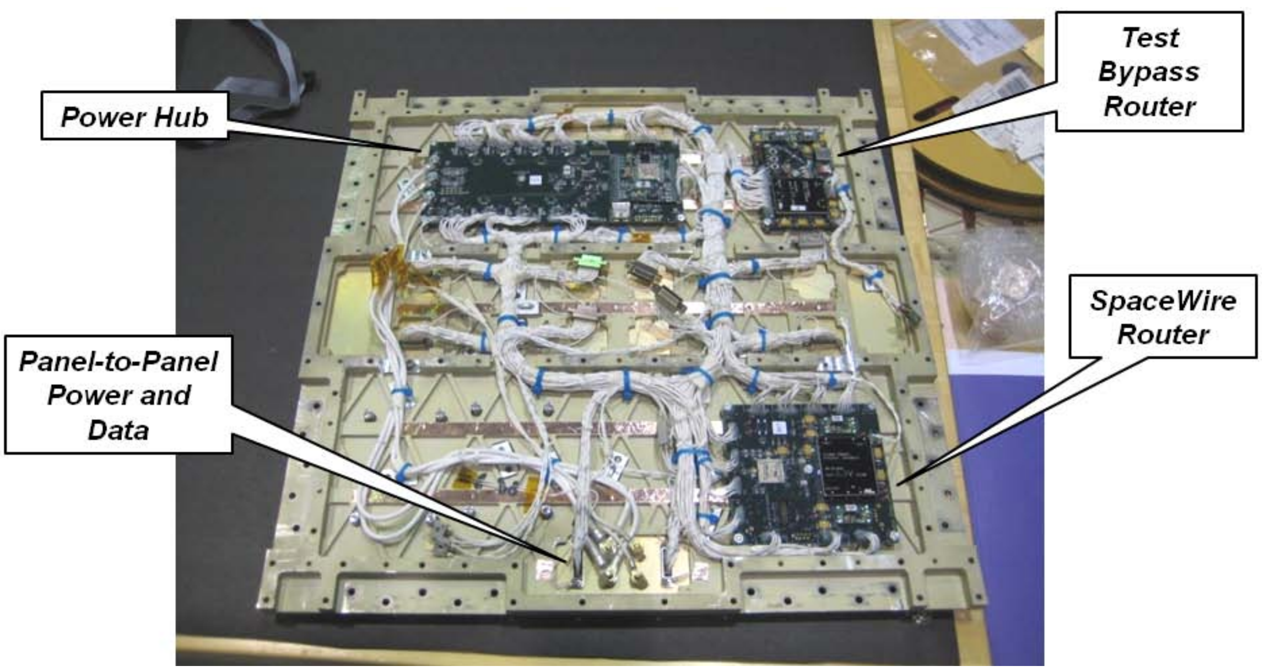

Figure 34. PnPSat-1 Panel Interior [28]

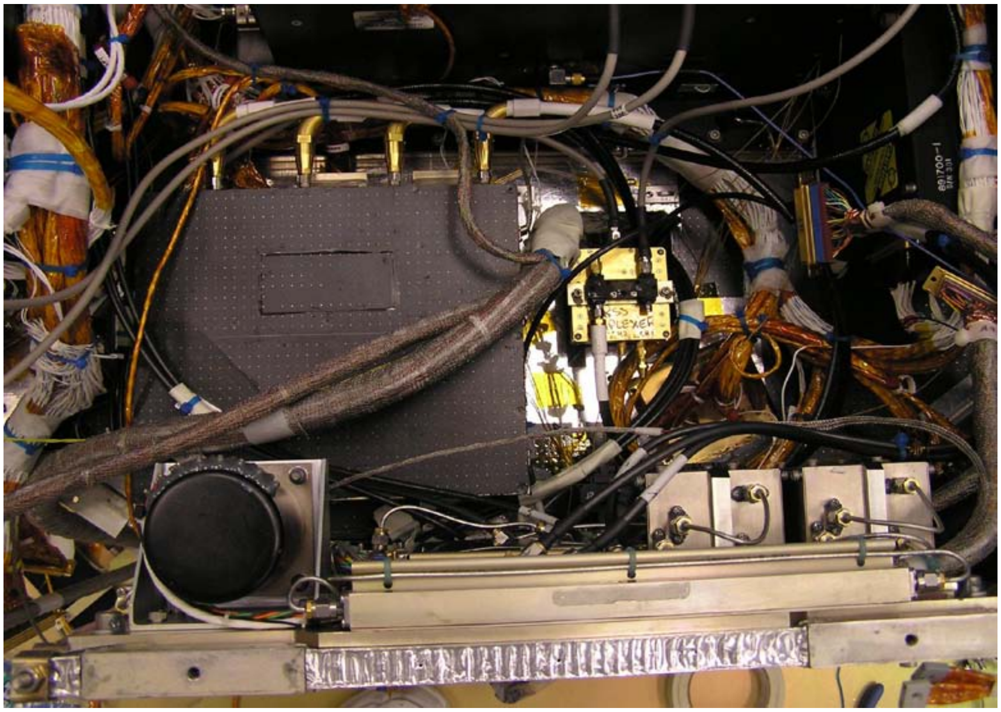

Figure 35. TacSat-2 Interior [28]

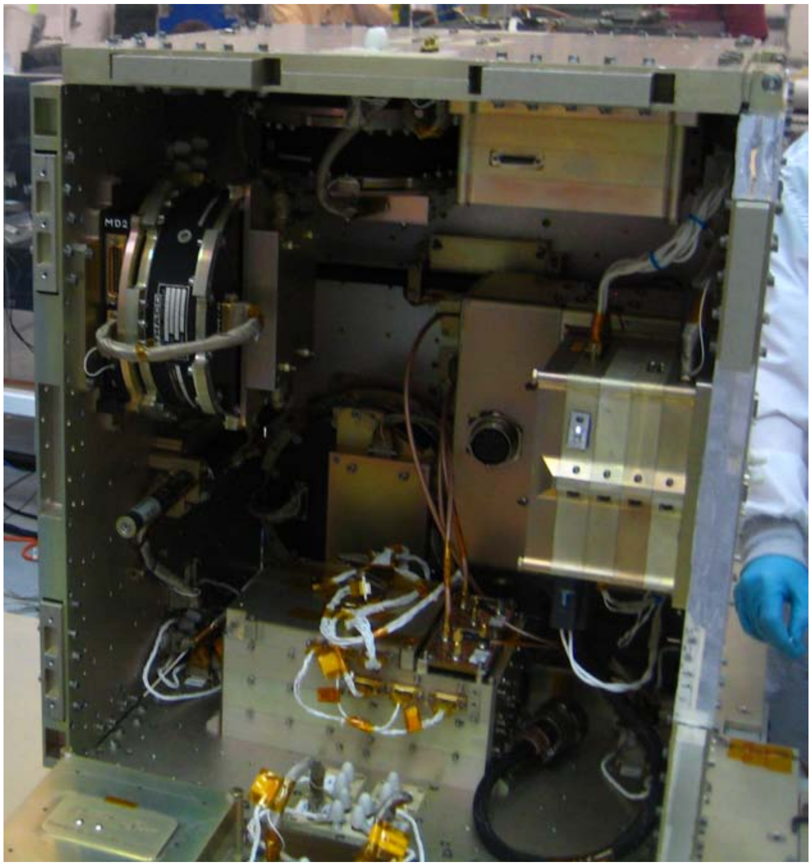

Figure 36. PnPSat-1 Interior [28]

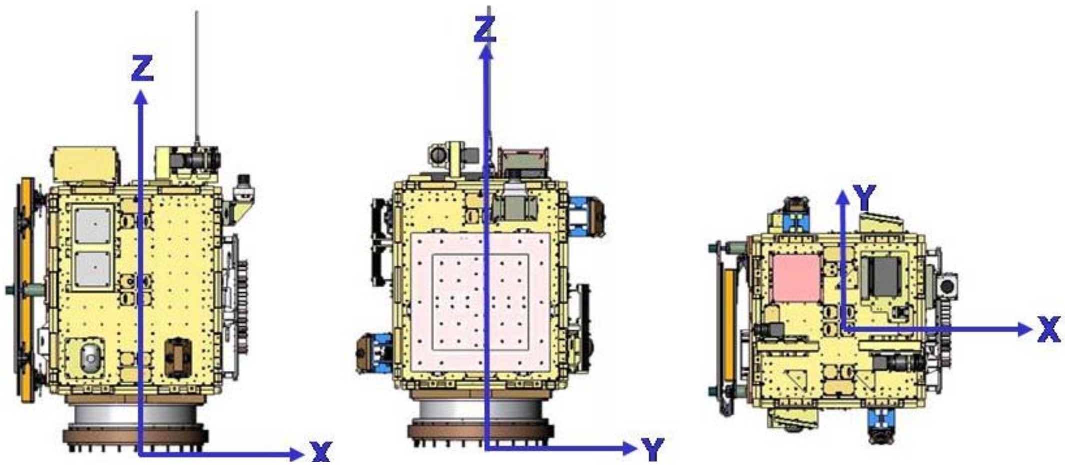

Figure 37. PnPSat-1 Coordinate Frame [29]

3.2.2 Avionics

PnPSat-1 Space Plug-and-Play Avionics (SPA) infrastructure includes:

- Appliqué Sensor Interface Module (ASIM) (one per component) – *Data, power, ground, and time sync interface for each component; Contains component-specific xTEDS, the device description file similar to a driver;*

- Robust Power Hub (one per panel, Figure 34) – *Provides power distribution to all endpoints;*

- SpaceWire Router (one per panel, Figure 34) – *Provides high speed data interconnectivity between all endpoints;*

- Hardware in the Loop (HWIL) Router (one per panel, Figure 34) – *Provides "test bypass" access during any stage of integration for one component or the entire spacecraft to a singular simulation tool.*

3.2.3 Software

The Satellite Data Model (SDM) is the PnP-enabling software. SDM's primary job is upon system startup - registering the components and applications along with their location in the SPA network, and learning their command and telemetry parameters via their xTEDS. This enables SDM to make and manage the necessary connections between components and applications (Figure 38). For example, if an ADCS application requires magnetometer telemetry, SDM will make the connection between the ADCS software and the magnetometer ASIM software. Once the connections are made at startup, SDM is largely inactive, until another connection is requested.

An example of a connection that may be requested after system startup is the request of telemetry data at the ground station. To request telemetry, a user (ground user, device, or application) is said to "subscribe" to that data. Conversely, the user can also "unsubscribe" the data when it is no longer needed. In an operational satellite, the use of subscriptions can ensure that the bandwidth, both on the SPA network and in the downlink, is being utilized by only the necessary or highest priority data.

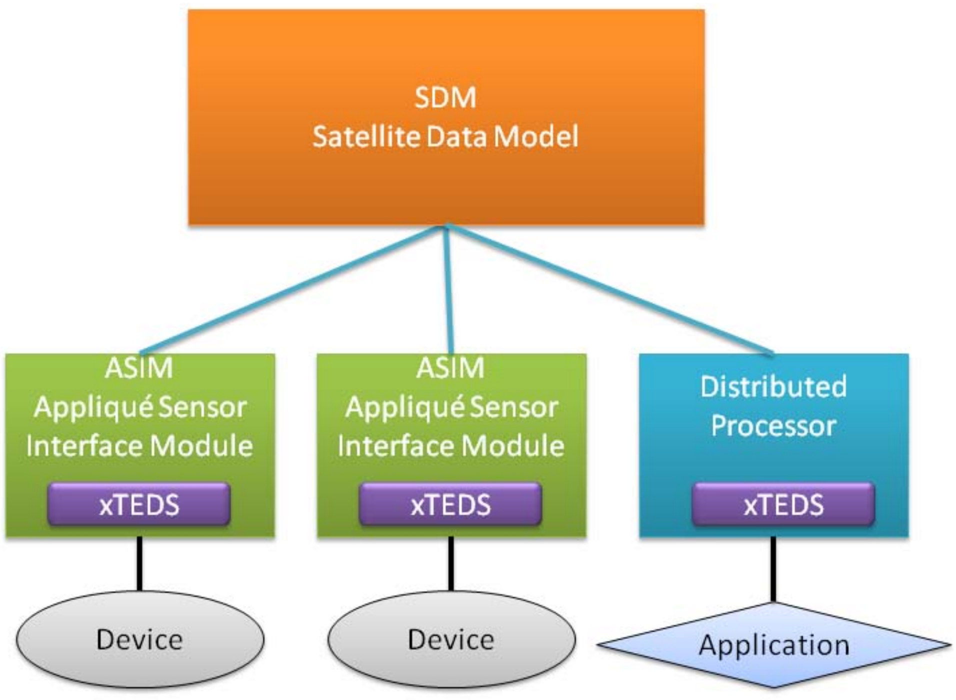

Figure 38. Satellite Data Model Interaction with Components and Applications

3.2.4 Hardware Components

Components can be made PnP-compatible by adding an ASIM to the device. The ASIM acts as the interface between SDM and the device and is the enabler for self-configuration and description. The ASIM houses the xTEDS, a file which describes the device completely – command and data, usage, and operational constraints. If a component is PnP-compatible, it should be able to be integrated into any PnP bus with little effort. For this experiment, we have a limited number of PnP-compatible components. The list of available components and their mass is given in Table 15. While this list comprises the available components, it is possible that all components may not be utilized in every trial. The S/C configuration for each trial will be detailed in Chapter 4. The baseline configuration is shown in Figure 39.

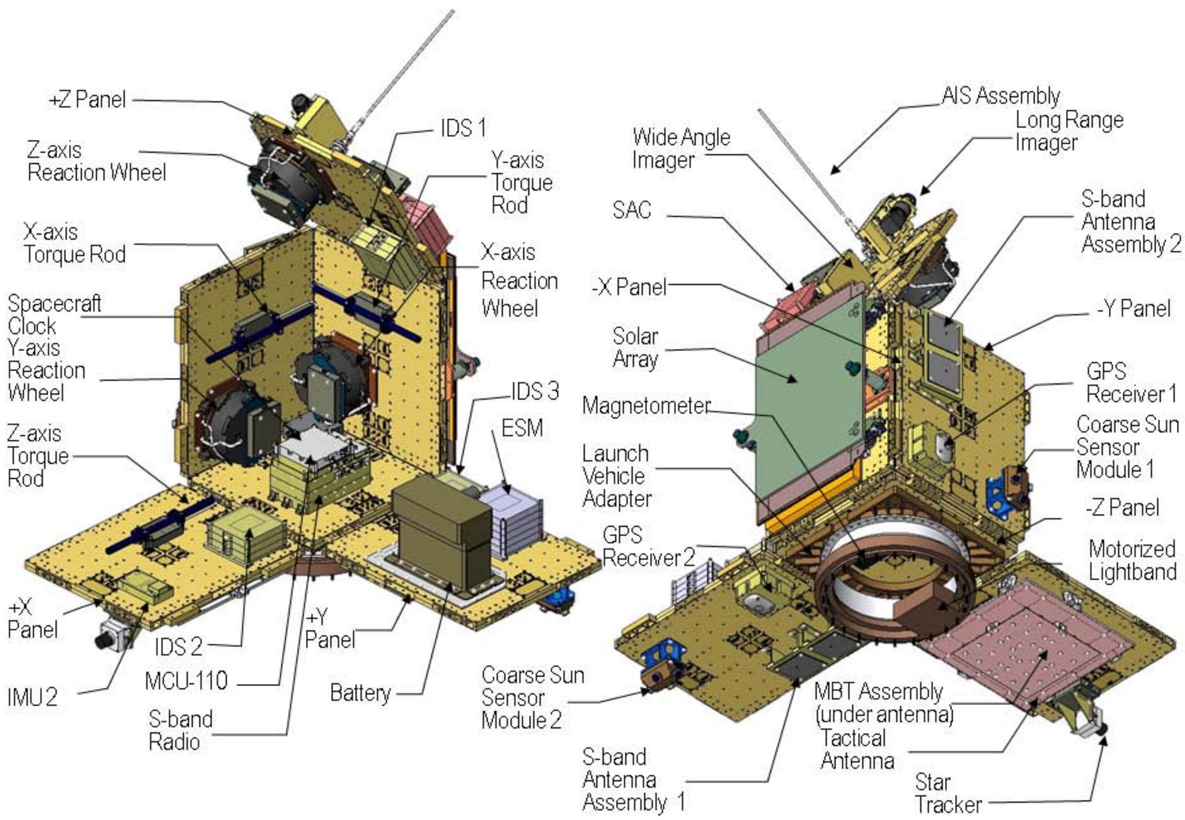

Figure 39. Baseline S/C Configuration [29]

Table 15. Available PnP Components [29]

Subsystem	Component	Quantity	Mass Each (kg)	Total Mass (kg)
Structure	Bottom Deck	1	6.486	6.486
	Top Deck	1	6.396	6.396
	Thru-Side Panel	1	7.230	7.230
	Common Side Panel 1	1	7.170	7.170
	Common Side Panel 2	1	7.170	7.170
	Common Side Panel 3	1	7.170	7.170
	Launch Vehicle Adapter and Hardware	1	4.185	4.185
	Motorized Lightband and Hardware	1	2.943	2.943
	Structure Subsystem Total			**48.750**
Power	Battery	1	10.420	10.420
	Energy Storage Module (ESM)	1	2.506	2.506
	Solar Array	1	7.395	7.395
	Solar Array Controller (SAC)	1	1.762	1.762
	Power Subsystem Total			**22.083**
Avionics	Intelligent Data Store (IDS)	3	1.200	3.600
	Real Time Clock (RTC)	1	0.392	0.392
	Avionics Subsystem Total			**3.992**
ADCS	Reaction Wheel Assembly	3	4.521	13.564
	Torque Rod	3	0.720	2.161
	Magnetometer	1	0.480	0.480
	Coarse Sun Sensor (CSS)	2	0.524	1.048
	Inertial Measurement Unit (IMU)	1	0.360	0.360
	Star Tracker	1	0.820	0.820
	GPS Receiver	2	0.696	1.392
	ADCS Subsystem Total			**19.825**
Telecom	UHF Radio	1	0.775	0.775
	UHF Antenna	1	1.900	1.900
	S-band Radio	1	4.170	4.170
	S-band Antenna Assembly	2	1.135	2.270
	Telecom Subsystem Total			**9.115**
Experiments	Long Range Imager	1	1.290	1.290
	Wide Range Imager	1	1.100	1.100
	Automated Identification System (AIS)	1	1.080	1.080
	Experiment Total			**3.470**
Thermal	Multi-Layer Insulation (MLI)	1	1.690	1.69
	Thermal Subsystem Total			**1.690**
Harnessing	Component and Experiment Harnessing	1	0.850	0.850
	Harnessing Subsystem Total			**0.850**
GSE	Lifting Blocks	3	0.098	0.294
	Direct Connect Box	1	0.340	0.340
	Spacer Ring	1	2.735	2.735
	GSE Component Total			**3.369**

Spacecraft Total	**113.143**

3.2.5 *Limitations of the Test Article*

As mentioned previously, PnPSat-1 was never flight-qualified due to cost constraints, and is now used as a testbed for AFRL SPA technology development and for ORS office exercises. There are violations of the two assumptions that the flight model is identical to the qualification model and that all components are fully qualified. These limitations are described below:

- Demo configuration does not match the QM configuration exactly:
    - The MCU110 radio encryption device is not in the demo configuration. Due to security issues and concerns about extending the lifetime of flight hardware, the MCU110 will not be installed for the demonstration. The MCU110 is a relatively small mass (680 g) as compared to S/C mass (113 kg) and should not significantly affect any system level properties.
    - Due to concerns about extending lifetime of flight hardware, the star tracker was removed from the demonstration. A mass model is in its place for all tests.
- Most components are not flight qualified and the PnPSat-1 system has not been qualified launch ready. This is a violation of the assumption that all components are space qualified. This presents a complexity to the demonstration in that the components may fail from an unknown cause.
- Payload build and test timeline not fully demonstrated - assembling, maneuvering, calibrating, aligning sizeable or sensitive payload could increase Rapid AIT timeline and complexity significantly.
- PnPSat-1 is smaller and less complex than envisioned ORS-class satellites. Scaling up the AIT timeline may not necessarily be linear since bus design and payload requirements may be more complex.
- Facility layout may not be conducive to Rapid AIT. Ideas may come out of this demo on how to more efficiently design an integration facility for Rapid AIT.
- The solar array must be removed from PnPSat-1 for walkout and illumination tests. Removal and reinstallation of the array breaks the configuration of the satellite post-vibration test and adds time to the process.
- Thermal blanketing is not realistic with current technology or processes. PnPsat-1 already has fit-checked blankets, and creating new blankets will not be demonstrated.
- Vibration tests will be conducted to 6dB less than ESPA acceptance levels. While this change will not affect the determination of the primary structural modes, these levels may not be adequate to find workmanship errors.

4. Results and Analysis

This chapter presents the results and analysis of the Rapid AIT Demonstration. First, a summary level description of each trial is given. Then, test results and lessons learned are presented.

4.1 Trial Summaries

There were six Rapid AIT trials conducted during this demonstration, April - December 2009. Table 16 describes the S/C configuration, personnel responsibilities, date, purpose and duration for each of the Rapid AIT trials. The baseline qualification tests conducted at AFRL prior to the start of the Rapid AIT Demonstration is referred to as "Trial 0." The following subsections will detail the activities of each trial.

Table 16. Rapid AIT Demonstration Trial Summary

Trial	Date	Purpose	Rapid AIT	Validation Tests	Rapid AIT Duration
0: Baseline Configuration "Qualification Model"	Feb 09	Traditional set of tests to Qualify Design	No	Yes	Multiple weeks
1: Baseline Configuration* Team A Leads, Team B Training	9-11 Apr 09	Process and Procedure Validation; Train Team B personnel	Yes	Yes	7:02 Assembly; 21:58 Total
2: Baseline Config.* (RS7) Team A Leads, Team B Assists	28-30 Apr 09	Timed Trial; Optimize Procedure	Yes	No	4:10 Assembly; 18:28 Total
3: Baseline Configuration* Team B Leads, Team A Assists (Q/A Only)	11-13 May 09	Personnel Investigation - Training, Skill Set, Number of Personnel; Optimize Procedure	Yes	Yes	9:10 Assembly; 26:04 Total
4: Sun-Sync AIS/Imaging Config.* Team B Leads, Team A Assists	8-10 Jun 09	New Configuration Using Same Component Set	Yes	Yes	6:20 Assembly; 22:07Total
5: Sun-Sync AIS/Imaging Config.* (Media Day) Both Teams, select members	23 Jun 09	Timed Assembly and Functional Test; New Configuration; Personnel Skill Set; Optimize Procedure	Yes	No	1:28 Assembly; Total Undefined
6: Multi-Spectral Imaging Configuration* Both Teams, select members	14-17 Dec 09	Build and Integration of New Payload (MSI Imager), Timed Assembly	Yes	No	2:51 Assembly; Total Undefined

*Star tracker mass model installed rather than Flight Model; MCU-110 only installed for TVAC.

4.1.1 Trial 0 (Baseline)

Trial 0, the baseline qualification tests, were conducted at AFRL in February 2009. The data gathered in those tests was used as a comparison for data gathered in the Rapid AIT trials. The S/C configuration for the Trial 0 environmental tests is shown in Section 3.2.4. The total S/C mass is 113.1 kg.

4.1.2 Trial 1

Trial 1 was the first implementation of the Rapid AIT Demonstration test plan. Team A, the experienced PnPSat-1 personnel, executed PnPSat-1 AIT and used this trial to train Team B. They also used this time to test procedures and verify GSE setup. This exercise resulted in a change to the level of detail in the procedures to provide more information for Team B.

The S/C configuration was identical to the Trial 0 configuration with a few minor exceptions. The star tracker was removed and returned to AFRL for use on a flight program. A mass model is used in its place. The MCU-110, the S-Band encryption device, was not used in any of the Rapid AIT tests. Because the MCU-110 is an encryption device, it must remain in a safe unless being monitored by cleared personnel. Because of the security concerns of constant monitoring, it will only be installed during TVAC testing, when personnel must accompany the S/C at all times anyway.

4.1.3 Trial 2 (RS7)

Trial 2 was conducted concurrently with the Responsive Space 7 Conference (RS7) and was broadcast to the conference attendees. Team A conducted the activities, but had assistance from Team B. The S/C configuration is the same as Trial 1. All activities in the Rapid AIT test flow were completed, but a validation test series was not completed due to time constraints.

4.1.4 Trial 3

This was the first trial led by Team B. The configuration was identical to the previous trials. Team B struggled with the lack of detail in the assembly procedure, resulting in lengthy assembly duration. The format and level of detail was adjusted throughout the trials in attempt to find an appropriate format. Suggestions on procedure format can be found in the Lessons Learned.

4.1.5 Trial 4 (Configuration Change)

Trial 4 included the same hardware components used in Trials 0-3, but many components were relocated on the bus structure. In this trial, Team B led all Rapid AIT activities, and Team A provided quality assurance.

There was a very good demonstration of using the computer-controlled cutting table to create patterns for thermal blankets and radiator tape. The computer aided drawing (CAD) solid model was used to generate patterns that were cut and applied real-time during Rapid AIT. An old version of SolidWorks software was installed on the computer for the cutting table. Once the model was converted, the tapes were cut in a matter of hours. Also, a simplified thermal model was created for the new configuration in one-half day for comparison with the TVAC data.

4.1.6 Trial 5 (Media Day)

As Trial 5 was primarily a media event, only the assembly and functional tests were executed. The configuration was identical to Trial 4, minus a faulty processor. Assembly members for this trial were selected from both Team A and Team B, based on skill set.

4.1.7 Trial 6 (Additional Payload)

A new PnP-compatible imaging payload was provided for Trial 6 which can be seen in Figure 40. The payload was delivered in a modular state, with options for various spectral bands and resolutions. The Rapid AIT team included members of both Team A and Team B, as well as a payload team.

At the start of the trial, the imager configuration was selected, and the payload team began assembly and test of the imager while the S/C bus was being assembled. Integration of the payload to the S/C bus required different GSE than used previously, but none of the GSE was non-standard equipment for a typical S/C integration facility. The complete assembly duration of the S/C was on the same order of magnitude as the previous trials. A payload functional test was completed a part of the bus functional test. An attempt to take images of the mountains in the distance proved quite difficult and was not successful due to the focal length of the imager. While using a test setup for calibration or functional testing is not as interesting as imaging a real scene, it may be necessary given hardware and timeline constraints. Imager calibration and alignment were not considered in this experiment and should be investigated in future demonstrations.

The payload was a developmental model and was not fabricated to withstand environmental tests. As such, no vibration or TVAC tests were completed on this configuration.

This trial also included mission operations rehearsals using the Chileworks common ground system. The rehearsals overlapped the factory compatibility test (FCT) in attempts to condense the Rapid AIT timeline and provide the operations team with more rehearsal experience. The geographical separation of the AIT, operations, and launch teams, as envisioned by ORS, creates a problem of situational awareness. Consideration should be given to create a system (i.e. telephone, web-based) by which all teams can maintain the schedule and work together during FCT/rehearsals.

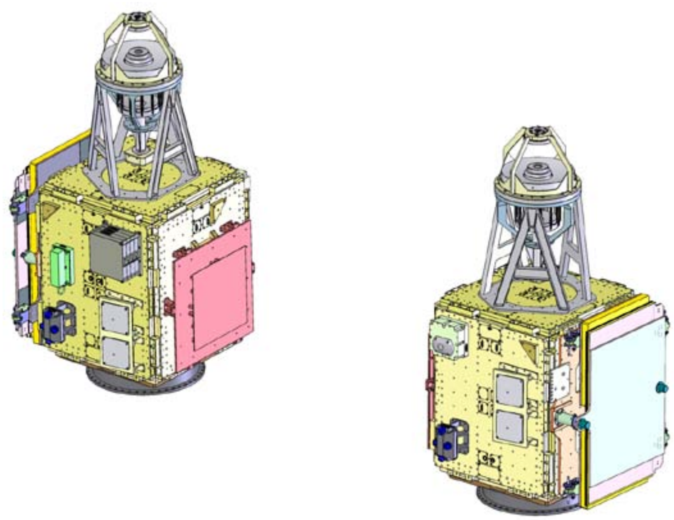

Figure 40. PnPSat-1 Configuration for Trial 6 [29]

4.2 Test Results

A primary goal of the Rapid AIT Demonstration was to investigate the influences on AIT timeline. Another goal was to determine it the Rapid AIT activities are sufficient to detect discrepancies/anomalies. The analysis of the Rapid AIT duration and anomaly detection is given first. Following that analysis, the data from the vibration, TVAC, and CG tests are discussed. These data may support the reduction of tests conducted at the system level. And finally, a compilation of lessons learned from the Rapid AIT Demonstration team and observers is provided.

4.2.1 Rapid AIT Duration

Table 17 shows a summary of the activities conducted in the Rapid AIT test sequence and their duration for each trial. It can be seen that the average total test time of 14 hr 35 min did not significantly vary throughout the demonstration indicated by a standard deviation of 20 min. The lack of variation is probably due to the automation of a majority of the tests. It can be assumed that human interaction increases test duration, so automating tests would be the most efficient use of time. However, it will be important for the test scripts to include adequate limit checking such that discrepancies do not go unnoticed.

The assembly activities were most variable, with an average of 5 hr 10 min, and standard deviation of 2 hr 52 min. Figure 41 highlights that assembly duration was influenced by personnel training and assembly team skill set more than configuration change, though configuration cannot be discounted. The assembly procedure format was also changed with each trial to find the format which provided the most efficiency.

As indicated in Figure 41, the assembly time was lowest when the assembly team was selected based on skill set and had been trained on PnPSat-1 assembly through previous trials. It should be noted that the configuration assembled in Trial 5 (1hr 28 min total assembly duration) had only been built once before. However, the level of detail of the assembly procedure was reduced to an assembly drawing and minimal text which proved more efficient than a text document with many steps. It appears that the most useful procedure included the assembly drawing and a table for each panel including the components to be installed with the respective number of fasteners, torque values, and endpoint connector number (where the component should be electrically mated).

Table 17. Rapid AIT Activity Duration Summary

Activity	Trial 1 (hh:mm)	Trial 2 (hh:mm)	Trial 3 (hh:mm)	Trial 4 (hh:mm)	Trial 5 (hh:mm)	Trial 6 (hh:mm)	Average (hh:mm)	Standard Deviation (hh:mm)
Assemble Internal Components to Bus Structure	3:36	02:24	04:57	02:50	00:45[1]	01:22	2:39	01:31
Bus Functional Test, Internal Components Only	0:50	00:34	01:14	00:40	00:34	00:50	0:47	00:15
Assemble External Components to Bus Structure	3:30	01:46	04:13	03:30	00:43	01:29	2:31	01:23
Bus Functional Test, Complete	1:22	01:00	02:00	01:07	01:00	01:17	1:17	00:22
Mass Properties - Weight and CG	1:00	01:10	01:00	01:30	N/A	00:59	1:07	00:13
Workmanship Vibration Test	1:10	01:20	01:00	01:10	N/A	N/A	1:10	00:08
Solar Array Deploy and Illuminate Test	1:00	00:50	01:00	01:00	N/A	00:10[2]	0:57[3]	00:05[3]
Bus Functional Test, Complete	1:30	01:11	01:05	00:50	N/A	N/A	1:09	00:16
Mission Scenarios	8:00	08:13	07:35	08:00	N/A	3:00[4]	7:57[3]	00:15[3]
Closeouts, Blanketing[6]	2:00	01:45	02:00	01:30	N/A	N/A	1:48	00:14
Payload Build/Test	N/A	N/A	N/A	N/A	N/A	3:30	3:30	00:00
Total Assembly	***7:06***	***4:10***	***9:10***	***6:20***	***1:28***	***2:51***	***5:10***	***02:52***
Total Test	***14:52***	***14:18***	***14:54***	***14:17***	***1:34***	***3:06***	***14:35***	***00:20***
TOTAL RAPID AIT DURATION	***21:58***	***18:28***	***26:04***	***22:07***	***N/A***	***N/A***	***20:51***	***02:03***

[1]Bus structure pre-assembled; [2]Deployment only; [3]Does not include Trial 6; [4]2.5 orbits only; [5]Concurrent with mission scenarios

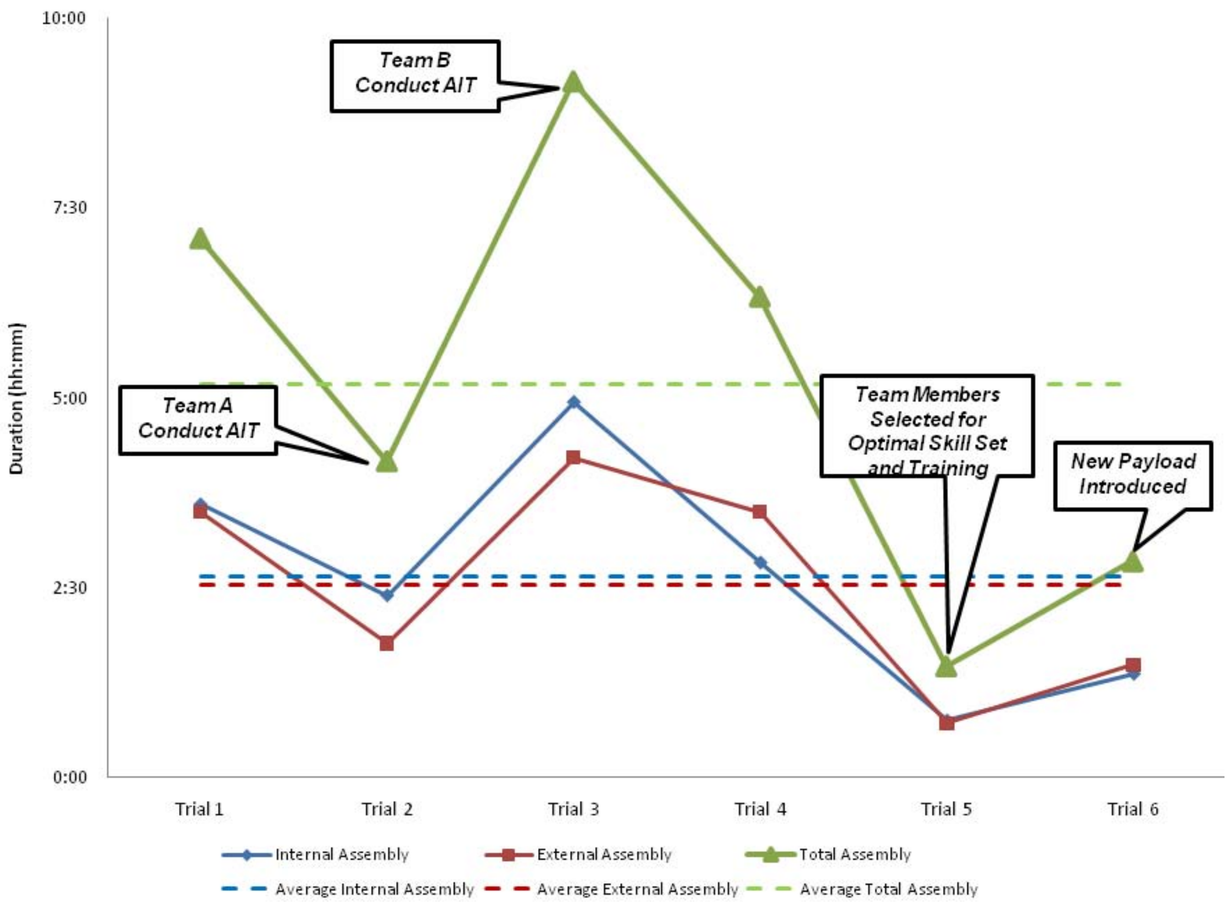

Figure 41. Rapid AIT Assembly Durations

4.2.2 Discrepancies

There were multiple discrepancies discovered during the Rapid AIT and Validation tests. The first discrepancy occurred in Trial 1 and was attributed to GSE failure. The umbilical command and telemetry (CMD/TLM) link on the S/C had intermittent failures throughout the trial. It was discovered that the serial card in one of the ground system computers was damaged during the demonstration setup. Compatibility issues with newer replacement computers continued to cause CMD/TLM problems. While this was not a result of activities unique to Rapid AIT, it provides valuable lessons to minimize GSE movement and to maintain spare, compatible GSE in inventory.

In addition, a problem was discovered with the S-Band Radio during the Trial 1 bus functional test. The source of the problem was not located within a reasonable time, so the S-Band portion of functional test was removed for the remainder of the trials. After the trial, additional troubleshooting showed that the problem was only evident in encryption-bypass mode. Because PnPSat-1 had previously been tested using encryption, this anomaly was not discovered sooner. However, it could be postulated that if the subsystem had been tested in all possible modes (bypass and encrypted) as part of the subsystem testing prior to Rapid AIT the discrepancy could have easily been discovered.

During the Trial 3 validation TVAC test the Solar Array Controller (SAC) ASIM repeatedly reset during hot cycles. Because the SAC is a developmental component and is not flight qualified, it is difficult to attribute the discrepancy to the activities of the Rapid AIT Demonstration. The SAC was moved to a cooler location in further trials to mitigate the anomaly. The SAC had undergone numerous TVAC tests at the time of failure, so it is unclear if pre-Rapid AIT tests would have precipitated or uncovered the failure.

In Trial 4, the umbilical CMD/TLM link failed during the first bus functional test. The problem reoccurred many times throughout the trial. Extensive troubleshooting indicated a hardware failure on one of the three onboard processors. Because the processors are developmental components and are not flight qualified, it is difficult to attribute the discrepancy to the activities of the Rapid AIT Demonstration. Regardless of the cause, this failure could be easily discovered in subsystem tests prior to Rapid AIT.

Trial 4 was the first attempt at building a new S/C configuration, the success of which relies heavily on loading correct software configuration files to the S/C and ground station. These configuration files describe the location/orientation of each component on the S/C.

Currently, the files are created and/or modified manually which can require many hours. During the mission scenario test, it was discovered that there were ADCS component orientation errors in the configuration files. While the anomaly was found in the Rapid AIT test phase and corrected, situations like this could possibly be avoided if the files were auto-generated in the mission planning process along with assembly drawings.

There were multiple PnPSat-1 discrepancies discovered during the Rapid AIT Demonstration. However, only one of those anomalies was not caught by the Rapid AIT tests. The SAC anomaly was discovered in validation TVAC tests and could not have been discovered in any other test. It is important to note, though, that the SAC failure occurred after many TVAC tests indicating that even with a more traditional test program the anomaly may not have been discovered. It is unclear whether the SAC anomaly was precipitated by Rapid AIT activities or if it was a result of degradation.

4.2.3 Vibration Test Results

The SpaceWorks PnPSat-1 structural finite element model predicts the first natural frequencies of 54.5 Hz and 55.5 Hz, using the maximum expected mass of 180 kg. The measured natural frequencies at the maximum expected mass were 52 Hz and 55 Hz. The first two modes are X and Y rocking modes. The X-axis mode is shown in Figure 42. The measured S/C mass of the baseline configuration of the Rapid AIT Demonstration is 113.1 kg, so the primary modes are expected to be measured at higher frequencies.

Because there is no structural model correlating to the baseline configuration, the Trial 0 data was the standard for comparison. In effect, the Trial 0 S/C is considered the Qualification Model to which we are comparing a Flight Model (Trails 1-6). Figure 43 plots the frequency response (first mode only) of the X-axis from each validation tests. The variance of the measured natural frequency between tests is low, but there is a noticeable change in amplitude in the Trial 4 test. The Trial 4 configuration was of mass to the baseline, but with a different mass distribution due to the relocation of components on the bus structure. The change in mass distribution explains the difference in response amplitude. The first two natural frequencies are shown in Table 18 for each vibration test conducted during the demonstration. It can be seen that the error in natural frequency from the baseline test is ≤3.13%. The Globalstar standards require ≤ 5% difference in natural frequencies to be qualified by similarity [22], among other criteria. Based on the Globalstar standards, the S/C built in Trials 1, 3, and 4 may be considered structurally identical. Although the Trial 4 configuration was quite different, the natural frequencies were within the 5% threshold. This finding may suggest that an improperly built S/C would not be caught by the comparison of natural frequencies alone. However, the response at the first natural frequency in Trial 4 is clearly different than the previous 3 trials, as can be seen in Figure 43, so a signature-based approach may still be appropriate. Further research should be conducted to determine more suitable metrics to qualify by similarity.

Both the Rapid AIT and validation vibration tests include a pre and post-random vibe sine sweep. The natural frequencies from these tests should be nearly identical, indicating no structural change occurred during the random vibe test. Figure 44 shows that the pre and post-random vibration data from the Trial 1 validation test (overlaid) are nearly identical. This is typical of all of the sine sweep data taken during the demonstration.

During the demonstration validation testing, a frequency response in the Z-axis was measured which was not seen in the system-level tests. Figure 45 shows the peak at 154Hz is not as prominent in the baseline as in Trials 1, 3, and 4. Troubleshooting of this change in structural response was inconclusive. The procedure used in the trials was not used on the baseline, however, which may suggest that strict adherence to a procedure results in more repeatable outcomes.

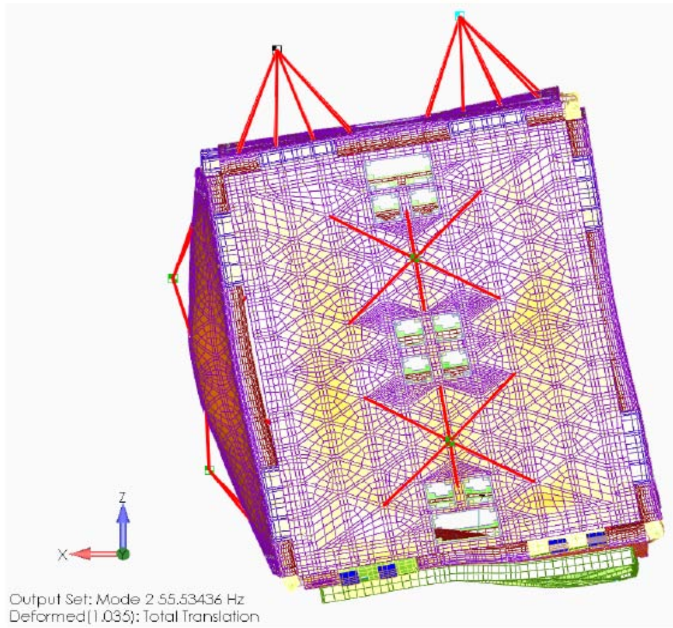

Figure 42. SpaceWorks Finite Element Model of PnPSat-1 First Rocking Mode (X-Axis) [30]

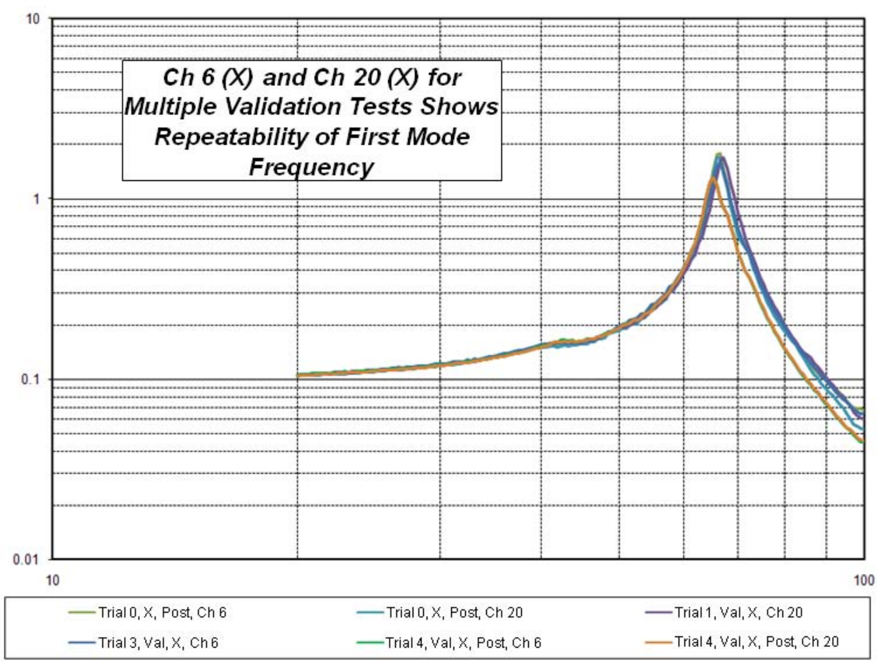

Figure 43. First Mode Frequency Comparison [30]

Table 18. Primary Mode Error from Baseline

Trial	X-axis Rocking Mode (Hz)	Percent Error from Baseline	Y-axis Rocking Mode (Hz)	Percent Error from Baseline
Trial 0 (Baseline)	**66.4**		**68.48**	
Trial 1 Rapid	67.09	**1.04**	69.9	**2.07**
Trial 1 Validation	67.09	**1.04**	67.78	**1.02**
Trial 3 Rapid	67.78	**2.08**	70.62	**3.13**
Trial 3 Validation	66.4	**0.00**	67.78	**1.02**
Trial 4 Rapid	65.73	**1.01 ***	69.9	**2.07 ***
Trial 4 Validation	65.05	**2.03 ***	68.48	**0.00 ***
*Different Configuration – identical structure and mass, different mass distribution.				

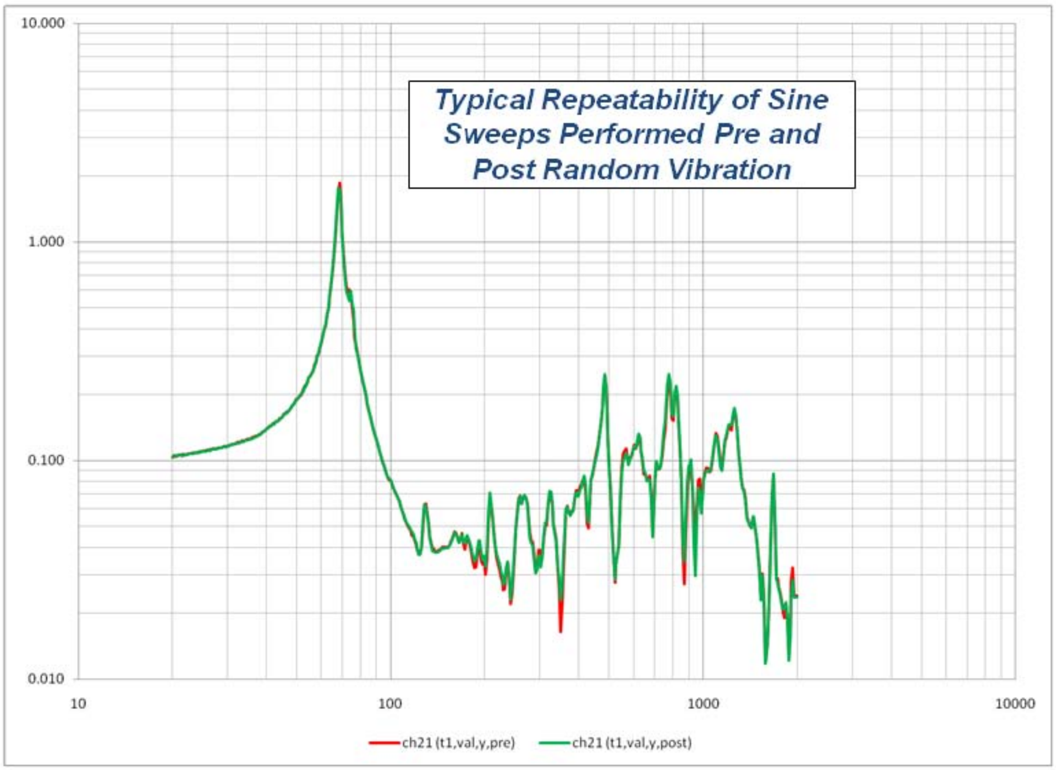

Figure 44. Pre- and Post-Random Vibration Sine Sweep Response [30]

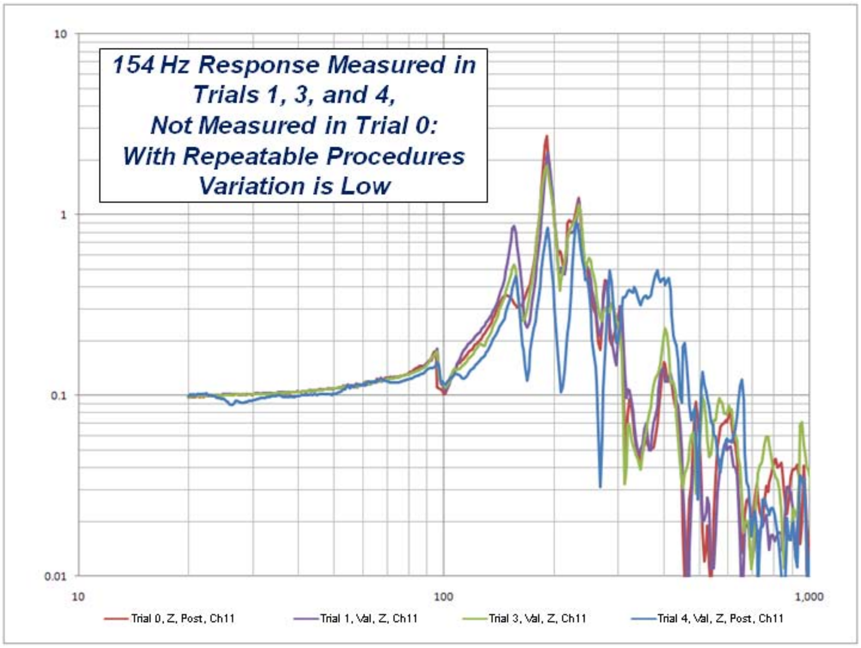

Figure 45. Z-Axis Frequency Response Comparisons [30]

4.2.4 Center of Gravity Measurement Results

Center of Gravity (CG) was measured in Trials 4 and 6, per the test description in Section 3.1.3.3. The measured values are compared to predicted values, as shown in Figure 46 and Figure 47. In both cases, the average measured location is within the Minotaur Launch Vehicle (L/V) requirement of 0.25in [34]. The CAD model used to predict these locations was a modified version of the baseline model.

It can be seen from comparing Figure 46 and Figure 47 that the dispersion in measured CG in Trial 6 was much greater than in Trial 4. The dispersion is most likely due to the use of an unleveled stand in Trial 6 while a leveled stand was used in Trial 4. However, the procedure calls for taking 13 measurements while rotating the S/C to eliminate the leveling error. The result can be seen in the accuracy between the average measured location and predicted location. In Trial 4, the accuracy is within 0.041in, and in Trial 6 the accuracy is within 0.051in. In this demonstration, it has been shown that one correlated CAD model has been modified to accurately predict the CG of a similar configuration within the launch vehicle requirements.

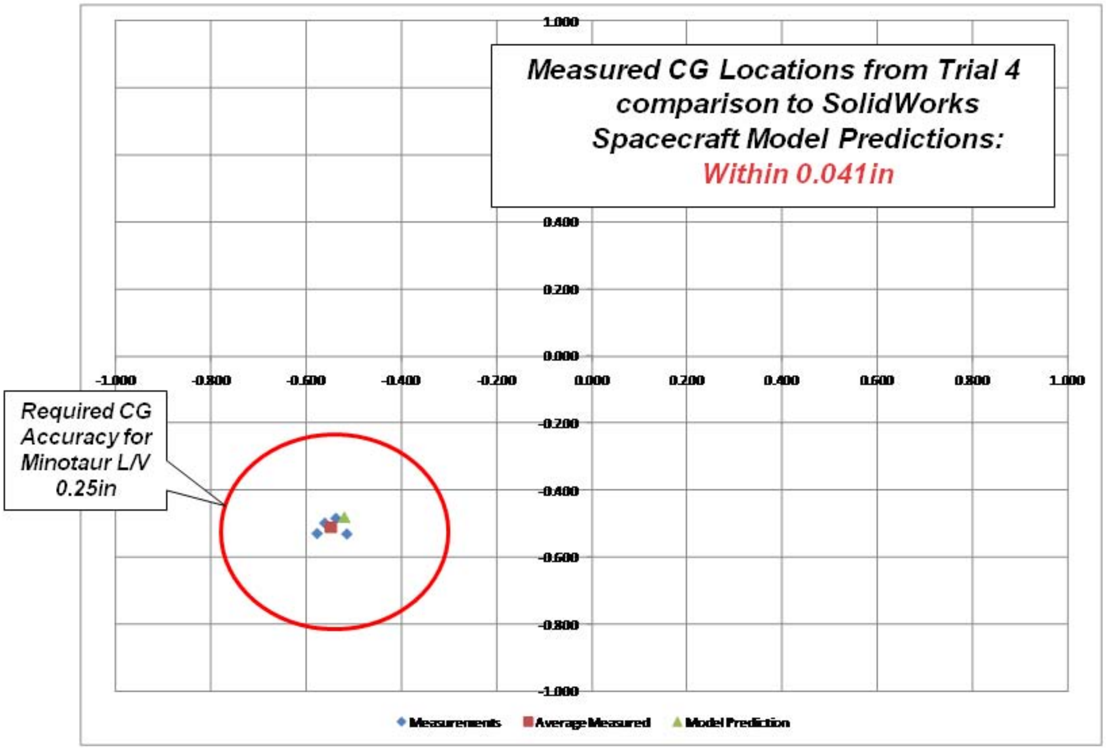

Figure 46. Trial 4 Center of Gravity

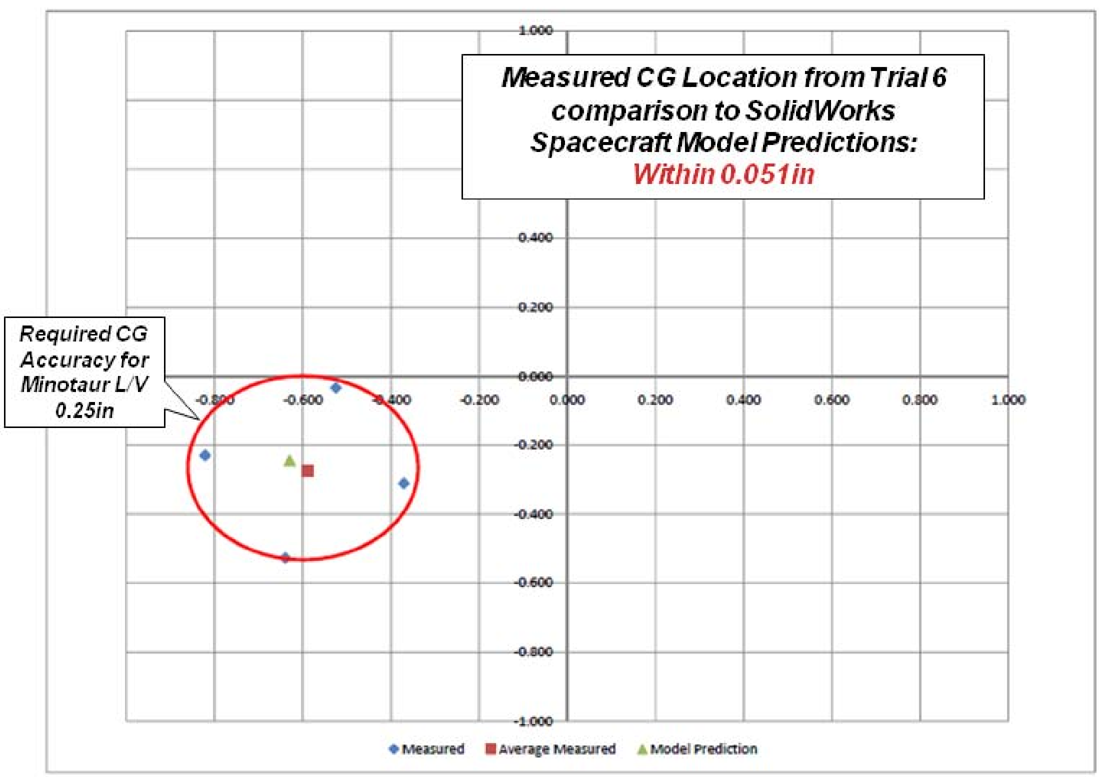

Figure 47. Trial 6 Center of Gravity

4.2.5 Thermal Balance and TVAC Test Results

Trials 1, 3, and 4 included a Thermal Balance/TVAC test during the validation testing, as described in Section 3.1.4.2. Trials 1 and 3 can be compared to the baseline (Trial 0) test since the configurations were very similar.

Table 19 shows the range of panel temperatures in steady-state conditions (thermal balance). There are eight internal temperature sensors per panel. The panel gradients in Trials 0, 1, and 3 are quite similar, indicating equivalent thermal properties. Trial 4 was conducted with a different component configuration, which did not include one of the three onboard processors. Because of the change in configuration, it would be expected that the S/C would have a different temperature profile. This difference can be seen when comparing the gradients from Trials 0, 1, and 3 to Trial 4. To validate the Trial 4 results, a simplified analytical model was created, based on the tuned model from Trial 0. As can be seen in Table 20, the model predicted the steady–state panel temperatures to within ±2.2° C and was created in a fraction of the time of the original (on the order of 1 day vs. 1 month). While there is no strict rule regarding thermal model accuracy, sources indicate that the objective is to obtain the greatest accuracy with the least cost/time. The Aerospace Corporation Spacecraft Thermal Handbook cited an example of a sufficiently-tuned model with ±3°C accuracy. ±3°C accuracy is considered adequate because margin is built into the thermal design to account for a given amount of inaccuracy. Based on the goal of decreasing cost/time, and the acceptable error, the simplified model created for Trial 4 was a success and may suggest that one well tuned analytical model could be used to very quickly create an accurate model for a variety of similar configurations. It should be noted that the timeline of creating a simplified model is dependent upon the engineer's experience and complexity of the S/C. PnPSat-1 is a fairly simple satellite, and the results in this case may not hold true for more complex S/C.

Table 19. Steady-State Panel Temperatures (Degree Celsius) [31]

	Trial 0 (Baseline)				Trial 1				Trial 3				Trial 4			
Shroud	-30		-60		-20		-60		-20		-60		-20		-60	
Panel +X	23	28	8	13	33	28	8	12	31	27	13	9	30	27	8	5
Panel -X	21	15	5	-1	26	20	5	-1	24	18	6	0	25	19	4	-3
Panel +Y	31	28	16	13	37	34	17	14	35	32	17	14	31	27	9	5
Panel -Y	20	15	4	0	25	20	4	-1	24	20	4	0	25	22	5	-1
Panel +Z	27	22	13	7	34	28	13	8	30	25	13	7	30	27	9	5
Panel -Z	28	21	13	6	32	27	14	7	32	26	14	7	28	22	8	0
Max	31		16		37		17		35		17		31		9	
Min	15		-1		20		-1		18		0		19		-3	
Gradient	16		17		17		18		17		17		12		12	

Table 20. Trial 4 Panel Temperatures Compared to Model Predictions (Degree Celsius) [31]

Shroud	-20					-60				
	Max	**Min**	**Ave**	**Predict**	**Error**	**Max**	**Min**	**Ave**	**Predict**	**Error**
Panel +X	30.0	27.0	28.5	28.0	0.5	8.0	5.0	6.5	5.6	0.9
Panel -X	25.0	19.0	22.0	24.2	-2.2	4.0	-3.0	0.5	1.8	-1.3
Panel +Y	31.0	27.0	29.0	28.8	0.2	9.0	5.0	7.0	6.5	0.5
Panel -Y	25.0	22.0	23.5	22.9	0.6	5.0	-1.0	2.0	0.5	1.5
Panel +Z	30.0	27.0	28.5	28.6	-0.2	9.0	5.0	7.0	6.3	0.7
Panel -Z	28.0	22.0	25.0	24.3	0.7	8.0	0.0	4.0	2.0	2.0

4.2.6 Lessons Learned

The lessons learned are a compilation of suggestions from various members of the demonstration team and observers. They are categorized into five areas of interest: S/C Design, Facility and Equipment, Personnel and Processes, Payload Integration, and Ground System and Operations. This section highlights the primary lessons, while the complete list can be found in Appendix E.

4.2.6.1 Spacecraft Design

- Design S/C and components for ease of testability to reduce test complexity and duration.
- Hard-coding or hand-coding of flight software or ground software should be avoided.
- Investigate automated methods for thermal blanket and radiator tape customization, such as the automated cutting table utilized in Trial 3.

4.2.6.2 Facility and Equipment

- A variety of common parts, like connector covers and cables of various lengths, should be readily available in assembly facility.

- Display procedures and drawings on large monitors in clean room to eliminate FOD and increase situational awareness of the entire team.

- Create a load distribution plan to ensure facility power is adequate for all required equipment.

- Ensure software on all equipment is up to date and compatible.

- Design S/C integration stand for ease of assembly and with multiple functions. For example, the mass and CG could be performed on the integration stand with incorporated load cells.

- Spare GSE must be stocked, to include compatible software and hardware, and should be regularly tested and calibrated.

4.2.6.3 Personnel and Processes

- Strict AIT discipline must be enforced to reduce unnecessary human errors. Quality Assurance Engineers should be utilized.

- Configuration Control is a full-time job and should not be left to Rapid AIT team.

- Number of personnel is not as critical as the correct mix of skill sets. Personnel should be trained in specific areas of expertise and perform only those operations to maintain proficiency and operate under clearly defined roles.

- It appears that the optimal format for the assembly procedure includes an assembly drawing and a table for each panel which lists the components, number of fasteners, torque value, and endpoint connector.

- A standard electronic interface control package should be delivered with each component into inventory, and should include assembly drawings and instructions, analytical models, operational instructions, and any required software (ex. xTEDS). The electronic package will allow auto-generation of configuration files, operations procedures, assembly procedures, etc.

- Automated test scripts should be a Pass/Fail test with adequate limit checking and error reporting.

- Communication/situational awareness between operations site, S/C AIT site, and launch site requires more consideration.

4.2.6.4 Payload Integration

- Payload test facility should be collocated with the S/C AIT facility, and should include test equipment with similar electrical and mechanical interfaces to the S/C bus.

- Alignment, calibration, and performance activities required after payload integration to S/C bus requires more investigation.

- The payload & bus should be designed to enable real-time image acquisition during integration and testing to reduce post-integration testing.

- The nature of the rapid call-up scenario did not limit payload testing capabilities because all possible configurations had been fully tested prior to being accepted into inventory. This should remain the model for Chileworks component stock.

4.2.6.5 Ground System and Operations

- There should be a standard, intuitive command/telemetry naming convention between all ground systems and components.

- Create an xTEDS format that provides enough component information for auto-generation of telemetry displays.

- Operations procedures should be predefined and included in the electronic standard interface control package.

- Operations rehearsals can be executed concurrently with AIT and launch site activities using simulations to familiarize the operations team with the S/C.

- The ground station should include an indicator of whether S/C telemetry is being received.

These results and lessons learned can be utilized when forming the Chileworks facility, operations, and Tier-2 S/C.

5. Conclusions and Future Work

As a result of perceived threats to critical U.S. space assets, the joint ORS Office was formed under the Office of Secretary of Defense to provide assured space access to Joint Force Commanders (JFC). There are multiple approaches to supplementing the JFC's needs, from employing an existing system to developing new technology. Tier-2 responses fall in the middle – using existing technology to deploy an asset within days-weeks of call-up. A Tier-2 response will require a departure from current Assembly, Integration, and Test (AIT) practices.

In the baseline ORS concept of operations, all components, subsystems, and bus configurations must pass all qualification tests to be accepted into inventory at their rapid response facility, Chileworks. It will be from this stock of fully-qualified components/subsystems that a Tier-2 S/C will be assembled. Because of the previous qualification, the newly assembled S/C, or flight model, will complete only a subset of less stringent acceptance tests – called Rapid AIT. The Rapid AIT Demonstration was sponsored to explore the minimization of AIT timeline to support a six-day call-up using this concept of operations.

The Rapid AIT Demonstration includes six trials, each of which include a Rapid AIT phase and a validation test phase. The Rapid AIT phase is designed to minimize the AIT timeline within ORS constraints. The validation test phase includes traditional tests, like 3-axis vibration and thermal vacuum (TVAC) testing. The purpose of the validation tests is to verify no errors were missed or precipitated by the Rapid AIT activities.

Both traditional and non-traditional satellite AIT practices were examined to gather lessons learned that are applicable to the ORS goals and constraints in development of the test plan. There are many standards and guidelines which, if strictly followed, would dictate a timeline that far exceeds the goals of ORS. There are, however, cases of rapid satellite AIT more akin to production lines that resulted in a manufacture rate of one satellite per week. For example, the Iridium, Globalstar, and ORBCOMM programs performed operations in parallel with each station, or island, providing a specific operation. Full qualification testing was conducted on initial articles, but the majority of flight articles were subjected to a smaller complement of acceptance testing. They also showed success by using automated test scripts and procedures. These are some of the lessons from industry that have been applied in the Rapid AIT test plan.

Using previous research, industry-accepted guidelines, lessons learned, expert knowledge, and standard industry practices, a test plan was developed by the Principal Investigator and various team members for the Rapid AIT trials. MIL-STD-1540 served as the basis from which the Rapid AIT procedure was created. Individual tests were modified, reordered, or removed for the purposes of meeting the ORS Tier-2 Rapid AIT timeline.

Test data, such as vibrational modes, thermal response, and center of gravity, from both the Rapid AIT and validation tests were compared to the baseline test data collected prior to the demonstration. Comparing measurements to a baseline data set to verify similarity of the flight model to the qualification model is referred to as a signature-based approach, which is similar to the approach taken in the Globalstar program. In addition, analytical models were used to predict thermal gradients and center of gravity locations for S/C configurations other than the baseline. The trials were timed to investigate the influence of personnel, training, and processes on AIT duration. Discrepancies were recorded during both Rapid AIT and validation tests to determine if Rapid AIT provides sufficient testing to catch anomalies. And finally, lessons learned were collected from the team with respect to S/C design, facility and equipment, personnel and processes, and ground system and operations.

5.1 Conclusions

A primary goal of the Rapid AIT Demonstration was to investigate influences on AIT timeline. By timing each trial, it was found that the primary driver to AIT duration was S/C assembly activities. The total testing duration had little variability, due to the automation of many individual tests. By examining the trend in assembly duration, the timeline appeared to be most influenced by personnel training, mix of skill sets in the assembly team, and efficiency of the assembly procedure. With an assembly team not familiar with PnPSat-1, the total assembly time was 9 hr, 10 min. In stark contrast, employing an intentionally selected team with PnPSat-1 training and a streamlined procedure, PnPSat-1 was assembled in 1 hr, 28 min.

Plug-and-Play (PnP) technology has proven to be a key enabler in reducing the Rapid AIT timeline because standard interfaces reduce the number of tools/equipment/time required for assembly. Another main draw to utilizing PnP components is the advertised flexibility of changing S/C configurations. However, changing S/C configuration was not without some difficulty. The PnP supporting software, such as configuration files, is updated manually for a change in S/C configuration. Updating the files required many hours and contained errors that resulted in testing anomalies. Manual updates are not realistic under the ORS time constraints and they result in unnecessary human errors. The process to update configuration files should be automated, and a configuration control program should be employed to mitigate human errors.

Another goal of this research was to verify if the tests in Rapid AIT were sufficient to detect anomalies prior to launch. There were multiple anomalies in the demonstration, but only one was not caught during Rapid AIT. The failure which was detected in a TVAC test occurred after many similar TVAC tests, so it is possible that a more traditional qualification program would not have provided additional mission assurance.

By examining data from the Rapid AIT and validation tests some conclusions can be made to support the reduction of tests conducted at the system level. Existing analytical models were updated for a variety of configurations to predict panel thermal gradients and center of gravity location. The updated thermal model accurately predicted temperatures at test locations on the bus structure to within ±2.2°C of measured for each sensor, which is considered acceptable by the Aerospace Thermal Control Handbook. The updated structural model predicted the center of gravity location well within the ±0.25 in launch vehicle accuracy requirement defined in the Minotaur User's Guide. These results indicate that well-tuned analytical models of a qualification model can be manipulated to accurately predict S/C properties of a variety of configurations and may provide confidence in a reduced test program.

Measuring natural frequencies in multiple vibration tests showed that with repeatable procedures consistent test results can be obtained. The consistency of results with repeatable procedures was highlighted in the Z-axis vibration tests. All of the demonstration tests showed a Z-axis response that had not been previously seen in the baseline test. The only difference between the demonstration and baseline tests was the strict adherence to a procedure during the demonstration. The Z-axis vibration data suggests that the use of repeatable procedures results in more consistent outcomes.

The consistency of the measured natural frequencies was again illustrated when comparing the response of the trial configurations to the baseline configuration. The comparisons showed that the first and second natural frequencies of all configurations were within 3.13% of the baseline test. In the Globalstar program, 5% deviation between qualification model and flight model natural frequencies served as a constraint for qualification by similarity. Because multiple S/C configurations met this constraint when compared to a single qualification model, more study should be given to the development of the metrics by which a S/C is qualified by similarity.

Finally, an extensive list of lessons learned from the Rapid AIT trials have been compiled for incorporation into the Chileworks concept of operations. For example, it was found that the number of personnel on the AIT team was less important than the correct mix of skill sets, and that the personnel should have well-defined roles. This is comparable to the ORBCOMM and Globalstar “island” concept of operations where the S/C was moved through stations which performed specific operations. Also, test discipline and situational awareness among team members is critical to decreasing the AIT duration.

Based on the analysis of the Rapid AIT Demonstration results, it is the author’s opinion that the ORS Office is on the right track to meeting the Rapid AIT goals. There are, however, many factors which can affect the outcome of the Rapid AIT process. Therefore, more research should be conducted to address some of the remaining questions.

5.2 Future Work

While many valuable lessons learned have been captured from the Rapid AIT Demonstration, there are still questions that can be answered with further research. While the thermal and structural models were used to accurately predict panel thermal gradients and center of gravity location for multiple S/C configurations, more research should be done on the accurate prediction of structural properties in various configurations. It is the author’s opinion that refined structural models may boost confidence in the reduction of vibration tests during Rapid AIT.

An investigation into the effect of S/C complexity on the Rapid AIT process may be of value to ORS. PnPSat-1 is a relatively simple satellite when compared to satellites being conceptualized by ORS Tier-2. As is shown in the studies described in Chapter 2, the relationship between test thoroughness, S/C complexity, and on-orbit failures is not linear. Consequently, conclusions drawn from this demonstration – model prediction accuracy, assembly and test durations, personnel requirements, etc. – need to be validated for a more complex S/C.

The optimal level of modularity was not investigated in this demonstration. Only the baseline vision of component-level modularity was exercised, though other options do exist. A lower level of modularity (component or piece part) provides more flexibility for the S/C design, but may result in longer assembly and test durations. A higher level of modularity (subsystem or bus) decreases the flexibility of S/C design, but could drastically reduce the Rapid AIT timeline. Further study of the modularity tradeoffs would be beneficial to determining the highest level of flexibility attainable within the ORS time constraint.

An investigation into payload calibration and alignment procedures should be done because they were not evaluated during this demonstration. Calibration and alignment activities can dramatically increase the Rapid AIT timeline. There are various methods for calibration and alignment which should be considered to determine the best approach for mission success within the ORS time constraint.

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Appendix A. System-Level Test Descriptions

This appendix lists the primary system-level tests discussed in this thesis. This information comes directly from MIL-STD-340A and SMAD.

Table 21. System-Level Test Descriptions

Test	Purpose	Description
Functional Test	Verifies that the mechanical and electrical performance of the vehicle meet the specification requirements, including compatibility with ground support equipment, and validates all test techniques and software algorithms used in computer-assisted commanding and data processing. Proper operation of all redundant units or mechanisms should be demonstrated to the maximum extent practicable.	Exercises all mechanical devices, and electrical and fiber-optic circuits through all mission phases. For at least one functional test in the qualification sequence, the vehicle will be operated through a mission profile with all events occurring in actual flight sequence to the extent practicable.
Electromagnetic Compatibility (EMC)	Demonstrates electromagnetic compatibility of the vehicle and ensures that adequate margins exist in a simulated launch, orbital, disposal, and return-from-orbit electromagnetic environment.	The test will demonstrate satisfactory electrical and electronic equipment operation in conjunction with the expected electromagnetic radiation from other subsystems or equipment, such as from other vehicle elements and ground support equipment.
Shock Test	Demonstrates the capability of the vehicle to withstand or, if appropriate, to operate in the induced shock environments. The shock test also yields the data to validate the extreme and maximum expected unit shock requirement.	In the shock test or series of shock tests, the vehicle will be subjected to shock transients that simulate the extreme expected shock environment to the extent practicable. All devices on the vehicle capable of imparting significant shock excitation to vehicle units will be activated.
Acoustic Test	Demonstrates the ability of the vehicle to endure acoustic acceptance testing and meet requirements during and after exposure to the extreme expected acoustic environment in flight. Except for items whose environment is dominated by structure-borne vibration, the acoustic test also verifies the adequacy of unit vibration qualification levels and serves as a qualification test for items not tested at a lower level of assembly.	The vehicle in its ascent configuration will be installed in an acoustic test facility capable of generating sound fields or fluctuating surface pressures that induce vehicle vibration environments sufficient for vehicle qualification. Appropriate dynamic instrumentation will be installed to measure vibration responses at attachment points of critical and representative units.
Vibration Test	Demonstrates the ability of the vehicle to endure vibration acceptance testing and meet requirements during and after exposure to the extreme expected environment in flight. Except for items whose response is dominated by acoustic excitation, the vibration test also verifies the adequacy of unit vibration qualification levels and serves as a qualification test for items that have not been tested at a lower level of assembly.	The vehicle and a flight-type adapter, in the ascent configuration, will be vibrated using one or more shakers through appropriate vibration fixtures. Vibration will be applied in each of 3 orthogonal axes, one direction being parallel to the vehicle thrust axis. Instrumentation will be installed to measure, in those same 3 axes, the vibration inputs and the vibration responses at attachment points of critical and representative units.

Test	Purpose	Description
Thermal Cycle	The thermal cycle test demonstrates the ability of the vehicle to withstand the stressing associated with flight vehicle thermal cycle acceptance testing, with a qualification margin on temperature range and maximum number of cycles.	The vehicle will be placed in a thermal chamber at ambient pressure, and a functional test will be performed to assure readiness for the test. The vehicle will be operated and monitored during the entire test, except that vehicle power may be turned off if necessary to reach stabilization at the cold temperature.
Thermal Balance	The thermal balance test provides the data necessary to verify the analytical thermal model and demonstrates the ability of the vehicle thermal control subsystem to maintain the specified operational temperature limits of the units and throughout the entire vehicle. The thermal balance test also verifies the adequacy of unit thermal design criteria.	The qualification vehicle will be tested to simulate the thermal environment experienced by the vehicle during its mission. Tests will be capable of validating the thermal model over the full mission range of seasons, equipment duty cycles, ascent conditions, solar angles, maximum and minimum unit thermal dissipations including effects of bus voltage variations, and eclipse combinations so as to include the worst-case hot and cold temperatures for all vehicle units.
Thermal Vacuum Test (TVAC)	The thermal vacuum test demonstrates the ability of the vehicle to meet qualification requirements under vacuum conditions and temperature extremes which simulate those predicted for flight plus a design margin, and to withstand the thermal stressing environment of the vehicle thermal vacuum acceptance test plus a qualification margin on temperature range and number of cycles.	The vehicle will be placed in a thermal vacuum chamber and a functional test performed to assure readiness for chamber closure. A thermal cycle begins with the vehicle at ambient temperature. The temperature is raised to the specified high level and stabilized. Following the high-temperature soak, the temperature will be reduced to the lowest specified level and stabilized. Following the low-temperature soak, the vehicle will be returned to ambient temperature to complete one thermal cycle. Functional tests will be conducted during the first and last thermal cycle at both the high- and low-temperature.
Mass Properties	Mass property measurements are taken to ensure onboard ADCS will be able to perform as required. Mass property requirements are dictated by launch vehicles for both weight and spin stabilization performance.	Weight, center of gravity, and moments of inertia are measured. Based on the final mass properties, balance and despin weights, if any, are calculated and installed. If the launch vehicle is spin stabilized during ascent, spin balance is performed.
Burn-In or Wear-In	The purpose of the burn-in test is to detect material and workmanship defects which occur early in the component life.	The total operating time for electronic and electrical component burn-in shall be 300 hours including the operating time during thermal cycling.
Factory Compatibility Test (FCT)	This test must be conducted to verify the operational ground stations can interface properly with the satellite.	Operational sequences of commands are sent to the S/C to set its operating modes in as realistic manner as possible. The data that will be transmitted from the S/C on orbit are recovered and checked to assure that the ground control software is designed and coded properly.

Appendix B. Requirements Verification Matrix

	Parameter or Metric	Existing Test	Validation / Verification				
					Test		
			Inspection	**Analysis**	Component Level	Rapid AIT	Qualifying Configurations
1	Attitude knowledge	ADCS Functional; MissionSim				MissionSim	x
2	Sun vector knowledge from sun sensors only	ADCS Functional; MissionSim				MissionSim	x
3	Position Velocity knowledge	ADCS Functional; MissionSim				MissionSim	x
4	GPS provides state vector for propagator	ADCS Functional; MissionSim				MissionSim	x
5	State Vector adjustable by ground command	ADCS Functional; MissionSim				MissionSim	x
6	ADCS supports sun-track mode	ADCS Functional; MissionSim				MissionSim	x
7	ADCS supports nadir pointing mode	ADCS Functional; MissionSim				MissionSim	x
8	ADCS supports rate-damping (inertial hold)	ADCS Functional; MissionSim				MissionSim	x
9	ADCS performs momentum dumping	ADCS Functional; MissionSim				MissionSim	x
10	Maximum slew rate	ADCS Functional; MissionSim				MissionSim	x
11	ADCS shall utilize reaction wheels	ADCS Functional; MissionSim	x				
12	ADCS utilizes torque rods for momentum dump	ADCS Functional; MissionSim	x				
13	Damp LV tip-off up to 2deg/sec	ADCS Functional; MissionSim				MissionSim	x
14	Autonomous sun point within 90min.					MissionSim	x
15	Separation	MissionSim				MissionSim	x
16	Power-on Reset	MissionSim				MissionSim	x
17	Minimum determination sensors available (sun sensor)	Off-nominal Scenario				MissionSim	x
18	S/C is 3-axis stabilized					MissionSim	x
19	ADCS Component polarities are verified as installed	ADCS BusFunc	x		x	BusFunc	x

20	Magnetometer direction/magnitude verified	ADCS BusFunc; Component Functional			x	BusFunc	x
21	Torque Rod commands will contingency expire after 1 sec	ADCS BusFunc; Component Functional			x	BusFunc	x
22	Inertial Measurement Unit responsive to S/C Motion	ADCS BusFunc; Component Functional			x		x
23	Monitor reaction wheel saturation and desaturate	ADCS Functional; MissionSim			x	BusFunc	x
24	Sun Sensor responsive to illumination	ADCS Functional			x	BusFunc	x
25	Provide an S-Band TT&C link	Comm Functional; MissionSim				MissionSim	x
26	Provide NSA Type 1 encryption on TT&C link	Comm Functional; MissionSim			x	MissionSim	x
27	Commanding for TT&C key changes	Comm Functional; MissionSim			x	MissionSim	x
28	S/C supports 8 TT&C contacts/day @ 10min. duration	Comm Functional; MissionSim				MissionSim	x
29	S/C allows S-Band commanding without FSW operating	Comm Functional; Off-nominal Scenario			x	MissionSim	x
30	Support ground initiated contacts	Comm Functional; MissionSim				MissionSim	x
31	Support scheduled S/C initiated contacts	Comm Functional; MissionSim				MissionSim	x
32	Authenticates TT&C commands using VCC	Comm Functional; MissionSim			x	MissionSim	x
33	TT&C Downlink & Uplink margins >3dB			x			
34	Output power	Comm Functional; MissionSim			x	MissionSim	x
35	Downlink Rate	Comm Functional; MissionSim					x
36	Uplink Rate	Comm Functional; MissionSim					x
37	Bit Error Rate	Comm Functional; MissionSim					x
38	Provide UHF tactical data link	Comm Functional; MissionSim				MissionSim	x
39	Provide AES software encryption on UHF link	Comm Functional; MissionSim			x	MissionSim	x
40	Commanding for UHF key changes	Comm Functional; MissionSim			x	MissionSim	x
41	S/C supports 8 UHF contacts/day @ 10min. duration	Comm Functional; MissionSim				MissionSim	x
42	S/C allows UHF commanding without FSW operating	Comm Functional; Off-nominal Scenario			x	MissionSim	x
43	Support ground initiated UHF contacts	Comm Functional; MissionSim				MissionSim	x
44	UHF Downlink & Uplink margins >3dB			x			
45	Output power	Comm Functional; MissionSim			x	MissionSim	x
46	Downlink Rate						x
47	Uplink Rate						x

48	Bit Error Rate						x
49	Provide UHF antenna pointing during contacts (ground antenna? ESA)	Comm Functional; MissionSim				Factory Compat	x
50	S/C detects LV separation	MissionSim; light band drop test				MissionSim	x
51	Autonomously deploy solar arrays	Deployment test; first motion; MissionSim				MissionSim/SA Deploy	x
52	Separation	Deployment test; first motion; MissionSim				MissionSim	x
53	Power-on Reset	Deployment test; first motion; MissionSim				MissionSim	x
54	Solar Array deployable by ground command	Off-nominal Scenario			x	MissionSim/SA Deploy	x
55	S/C command receptive in all mission phases	MissionSim				MissionSim	x
56	S/C shall discover & utilize SPA devices	Component Functional; MissionSim			x	MissionSim/BusFunc	x
57	S/C Re-registers components	Component Functional; MissionSim			x	MissionSim	x
58	Component Reset	Component Functional; MissionSim			x	MissionSim	x
59	Power-on Reset	MissionSim				MissionSim	x
60	Load FSW based on user-defined task list	MissionSim				MissionSim	x
61	Manage the on-board schedule of mission activities	MissionSim				MissionSim	x
62	Allow ground command to schedule contacts	Comm Functional; MissionSim				MissionSim	x
63	Structure Temperatures within limits	Power Functional; MissionSim		x	x	MissionSim	x
64	Component Temperatures within limits	Component Functional; MissionSim			x	MissionSim	x
65	Device ASIM provides watchdog reset	Component Functional; MissionSim			x	MissionSim	x
66	Provide control of telemetry points in RTSOH	MissionSim				MissionSim	x
67	Distributed system time and PPS to all devices	CDH Functional;MissionSim;Component functional			x	MissionSim	x
68	System clock adjustable by ground command	MissionSim			x	MissionSim	x
69	S/C supports RTSOH downlink	MissionSim				MissionSim	x
70	S/C supports SSOH downlink	MissionSim				MissionSim	x
71	Battery sized to support peak power demand	Power Functional; MissionSim		x			x
72	Solar array sized for orbit average energy needs	Power Functional; MissionSim		x			x
73	Battery charging does not require FSW	Power Functional; MissionSim			x	MissionSim	x
74	Endpoints provide settable OC trip	Power Functional; MissionSim			x	MissionSim	x
75	S/C attempts reset of tripped endpoints	Power Functional; MissionSim			x	MissionSim	x

76	Endpoints set in Config File to default to power-off		x				
77	Power hubs provide voltage and current monitors		x				
78	Main bus voltage & current monitor is provided		x				
79	Solar array voltage and current monitor is provided		x				
80	Component power states controlled	Power Functional; Component Functional;MissionSim			x	MissionSim	x
81	Transition to power-positive state at LV separation	Power Functional; MissionSim				MissionSim	x
82	Maintains power-positive state in nominal mission phases	Power Functional; MissionSim				MissionSim	x
83	Provide battery charging from solar array source		x				
84	Monitor battery state and prevent overcharge	Power Functional; MissionSim			x	MissionSim	x
85	Battery Charge/Discharge rate nominal	Power Functional; MissionSim			x	MissionSim	x
86	Monitor battery UV and autonomously sun point	Power Functional; MissionSim				MissionSim	x
87	Monitor battery UV and shed all loads at 26V	Power Functional; MissionSim				MissionSim	x
88	Monitor battery UV and reset trip flag at 27V	Power Functional; MissionSim				MissionSim	x
89	Monitor battery SOC and prioritize charging activity as appropriate	Power Functional; Off-Nominal Scenario				MissionSim	x
90	S/C provided test connector for HWIL testing		x				
91	S/C provides EPS single-point ground		x				
92	Primary structure fundamental frequencies	Vibration				Workmanship Vibe	x
93	Overall RMS level at XX location	Vibration					x
94	Steady State temps at hot and cold dwells	Thermal					x
95	S/C functions nominally at both hot and cold dwells	Thermal			x		x
96	S/C functions nominally in vacuum environment	Thermal			x		x
97	Bakeout- As a function of time/temp	Thermal					x
98	Conducted emissions	EMI/EMC		x			x
99	Radiated emissions	EMI/EMC		x	x		x
100	S/C meets LV physical envelope requirements	Mass Properties	x			Mass Props	x

Appendix C. Responsive Space 7 Surveys

Tuesday, 28 April 09

Organization: ______________________________

Role: ______________________________

☐ Military ☐ DoD Civilian ☐ Contractor ☐ Other: ______________________

Please circle one or more answer per question. Use the space provided to explain your answer or caveats / examples.

1. Considering payload complexity and post-integration alignment/calibration activities, which of the following missions do you think is the most difficult to attain within a 6-day call-up scenario? Why?
    a. Communications ______________________________
    b. Navigation ______________________________
    c. Weather ______________________________
    d. Surveillance ______________________________

2. What level of modularity do you think should be applied to Responsive Spacecraft?
    a. Very Modular – Components on shelf
    b. Somewhat Modular – Subsystems on shelf
    c. Not at all Modular – Fully-assembled bus on shelf

    ____
    ____
    ____

3. What do you believe is currently the driving factor of Launch Cost in the U.S.? Is this something that can be reduced for ORS launches?
    a. Management
    b. Hardware
    c. Processing/Facility Costs
    d. Timeline
    e. Other

    ____
    ____
    ____

4. What do you believe is currently the driving factor of Launch Schedule in the U.S.? Is this something that can be reduced for ORS launches?
    a. Management
    b. Safety/Security Guidelines
    c. Technical Difficulty
    d. Unique Payload Requirements
    e. Other

    ____
    ____
    ____

Thank you for your participation.

Wednesday, 29 April 09

Organization: ______________________________

Role: ______________________________

☐ Military ☐ DoD Civilian ☐ Contractor ☐ Other: ______________________

Please circle one or more answer per question. Use the space provided to explain your answer or caveats / examples.

1. Assuming a representative design has already been passed qualification tests, what level of risk is associated with NOT performing the following <u>system-level</u> tests:

	Low Risk				High Risk
a. Thermal Vacuum:	1	2	3	4	5
b. Vibration:	1	2	3	4	5
c. Electromagnetic Compatibility:	1	2	3	4	5
d. 200-Hr Burn-In:	1	2	3	4	5
e. Factory Compatibility:	1	2	3	4	5
f. Mission Scenarios:	1	2	3	4	5

2. If the following tests were not conducted, what failure modes might be missed?
   a. Thermal Vacuum: ______________________________
   b. Vibration: ______________________________
   c. EMC: ______________________________
   d. Burn-In: ______________________________
   e. Factory Compat: ______________________________
   f. Mission Scenarios: ______________________________

3. What level of modularity should be applied to Responsive Payloads?
   a. Very Modular – Pieces on shelf
   b. Somewhat Modular – Partially-assembled, uncalibrated payloads on shelf
   c. Not at all Modular – Fully-assembled, calibrated payloads on shelf

____

____

____

____

Thank you for your participation.

Organization: ______________________

Role: ______________________

☐ Military ☐ DoD Civilian ☐ Contractor ☐ Other: ______________________

Please circle one or more answer per question. Use the space provided to explain your answer or caveats / examples.

1. Which end of the spectrum should the ORS Office be investigating for Responsive Space Satellites:
   a. Common Bus Architecture – *One bus works for all ORS missions*
   b. Custom Bus Architecture – *The bus is customized for the mission, within the 6-day call-up window*

2. How often do you believe components/subsystems should be re-tested for functionality while in storage?
   a. Never
   b. Yearly
   c. Twice Yearly
   d. Monthly
   e. Other

3. How often do you believe Rapid AI&T personnel should retrain or conduct exercises to maintain readiness for an urgent need call-up?
   a. Continuously
   b. Yearly
   c. Twice Yearly
   d. Monthly
   e. Other

4. What factors would you consider when designing a Responsive Space Assembly, Integration, and Test facility? *(ex. Test equipment and layout)*

5. Do you envision Plug-and-Play interface standards being applied across the U.S. Spacecraft Industry? World-wide?

Thank you for your participation.

Appendix D. Responsive Space 7 Conference Survey Results

Introduction

As part of the Rapid Assembly, Integration and Test (AI&T) Demonstration, the Plug-and-Play Satellite (PnPSat) was built and tested during the 3 days of the 7th Annual Responsive Space Conference (RS7), 28-30 April 2009. The spacecraft build was completed in the Aerospace Engineering Facility (AEF), Kirtland AFB, NM, while a live webcast put the demonstration in the view of all conference participants. Daily spacecraft build updates provided interaction with the audience, explanation of the ORS Tier-2 concept, Rapid AI&T concepts and rationale, and areas requiring improvement or investigation. In an effort to capture suggestions or lessons from a broad experience base, the participants were urged to provide feedback throughout the conference.

There were multiple formats for audience participation and feedback:

- Via spacecraft build updates, where audience members were asked to define the satellite mission, test sequence, and offer advice;
- Through a blog, in which pictures and status of the spacecraft build were posted and questions to the build team were answered;
- Survey participation, geared toward the activities of the conference and the demonstration.

This report will summarize the results from the surveys completed at the conference.

Because the RS7 audience was exposed to daily ORS-led updates, conference proceedings, and had access to ORS team members for discussion, it can be assumed that the survey participants had an appropriate understanding of the background, context, and goals of ORS and were suitable participants. Surveys are being provided to other personnel in the spacecraft and launch industries to gather more data points. However, those results will be provided in a supplementary report as the participant background knowledge is unknown.

Survey Format

The surveys were designed to take only a short amount of time as participants would be filling them out at a booth in the exhibit hall. Three different surveys were handed out, one per day of the conference, approximately 4 questions each. Those surveys had the following focus areas:
Survey 1: Mission Planning and Rapid Launch
Survey 2: Spacecraft Test Requirements
Survey 3: Logistics, Training, and Facilities.

The three RS7 surveys can be found in Appendix C.

Most of the survey questions were formatted such that the participant could circle the answer most closely represented their opinion, each with an area for written discussion or explanation. In questions that had an “other” option, the most common responses will be discussed herein.

Survey Results

The answers from each survey received at the RS7 conference were compiled and each question's results will be discussed in this section. Each multiple choice question will have its results displayed graphically, depicting the percentage of each response. Results from short answer questions will be tabulated. In instances where a single participant circled two or more answers, each answer was treated as a separate response. This accounts for the potential mismatch between number of surveys received and number of responses.

Mission Planning

The following question was asked in Survey 1:

Considering payload complexity and post-integration alignment/calibration activities, which of the following missions do you think is the most difficult to attain within a 6-day call-up scenario? Why?

a. Communications
b. Navigation
c. Weather
d. Surveillance

14 surveys were collected this day, and there were 16 answers to this question. The breakdown of responses can be found in Figure 1.

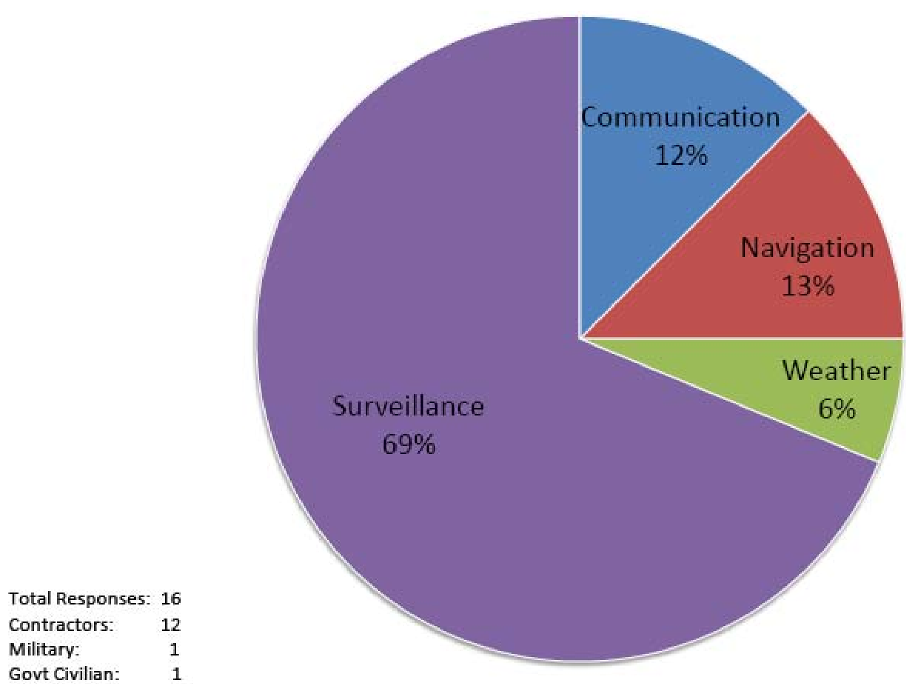

Figure 1. Most Difficult Mission for 6 Day Call-Up

It can be seen that, by far, surveillance was chosen as the most difficult mission to attain within a 6 day call-up scenario. The majority of responses indicated cleanliness requirements and alignment requirements for electro-optical imaging sensors as the drivers. One participant indicated Electromagnetic Compatibility (EMC) Tests may be required for RF-type sensors and may increase the timeline and AI&T complexity.

While surveillance sensors may have stringent alignment and cleanliness requirements, communications, navigation, and weather sensors have calibration activities of their own. Navigation sensors must have very accurate attitude control, and communication payloads will require complex EMC tests. Licensing and frequency management for communication satellites may also pose issues not easily resolved within a 6-day call-up.

It is certain that sensor calibration, if occurring during the 6-day call-up, would increase both AI&T timeline and complexity for any of the four categories.

Rapid Launch

The following questions were asked in Survey 1:

What do you believe is currently the driving factor of Launch Cost in the U.S.? Is this something that can be reduced for ORS launches?

a. Management
b. Hardware
c. Processing/Facility Costs
d. Timeline
e. Other

What do you believe is currently the driving factor of Launch Schedule in the U.S.? Is this something that can be reduced for ORS launches?

a. Management
b. Safety/Security Guidelines
c. Technical Difficulty
d. Unique Payload Requirements
e. Other

14 surveys were collected this day, and there were 15 answers to the question of Launch Cost and 17 answers to the question of Launch Schedule. The breakdown of responses can be found in Figures 2 and 3.

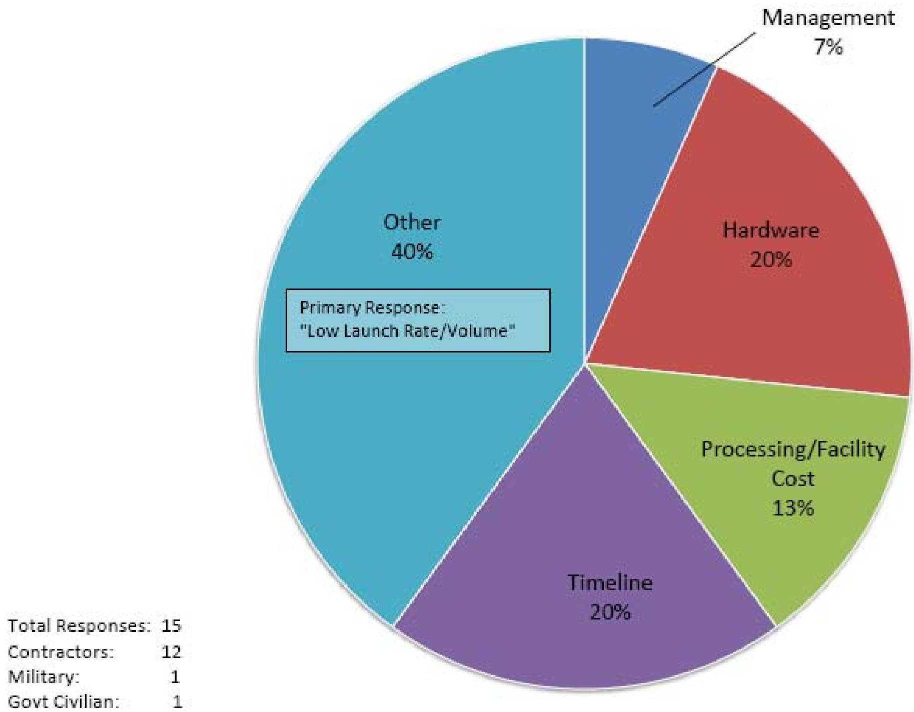

Figure 2. Current Driver of Launch Cost

The majority response to this question was none of the provided choices of Management, Hardware, Timeline, or Processing/Facility Costs. Within the group of participants choosing "Other" for their answer, the primary response was low launch rate/volume. There is a significant amount of infrastructure that must be maintained for launch operations, such as processing facilities/equipment, expirables, and launch control facilities/equipment. Since these overhead costs are spread amongst each customer, it makes sense that as number of customers increase the percentage of overhead cost to each customer decreases. Additionally, an increase in launch rate would perhaps decrease the amount of retraining and rehearsing prior to each launch, resulting in a decrease in both cost and schedule.

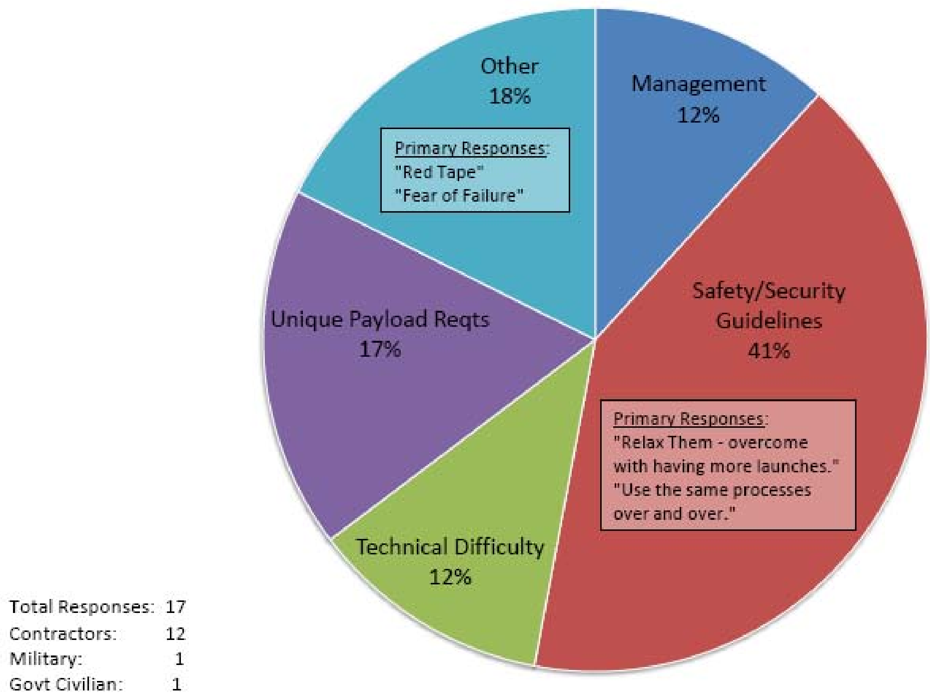

Figure 3. Current Driver of Launch Schedule

The primary response to this question indicated that Safety and Security Guidelines is the biggest driver to Launch Schedule. Currently, preparations begin 6 months – 1 year prior to the scheduled launch date. Much of this time is used to complete required safety/ security activities or documentation, currently unique to each spacecraft. All spacecraft and launch vehicle procedures must be reviewed and accepted by Range Safety personnel prior to use at the launch site. Some suggestions for mitigation of this schedule driver were "Relax them – overcome with having more launches," and "Use the same processes over and over." Surely, if launch rate increased processes would eventually become streamlined and personnel would maintain a state of readiness required for quick turn-around. And utilizing the same processes repeatedly would be vital. Some other mitigation techniques may be:

- Provide a set of range procedures common to each spacecraft type expected, with only few procedures unique to spacecraft based on specific payload/propulsion system/battery etc.
- Have well-defined security requirements that are applicable to all spacecraft within the given classification level.
- Integrate spacecraft to launch vehicle at the spacecraft integration facility, thereby removing unique procedures for various facilities/equipment, and differing safety and security guidelines.
- Co-locate spacecraft integration facility with launch facility.

Spacecraft Test Requirements
The following question was asked in Survey 2:

Assuming a representative design has already passed qualification tests, what level of risk is associated with NOT performing the following system-level tests:
(1=Low Risk; 5= High Risk)

a. Thermal Vacuum: 1 2 3 4 5
b. Vibration: 1 2 3 4 5
c. Electromagnetic Compatibility: 1 2 3 4 5
d. 200-Hr Burn-In: 1 2 3 4 5
e. Factory Compatibility: 1 2 3 4 5
f. Mission Scenarios: 1 2 3 4 5

13 surveys were collected this day, and there were 13 answers to the questions. The breakdown of responses can be found in Figure 4.

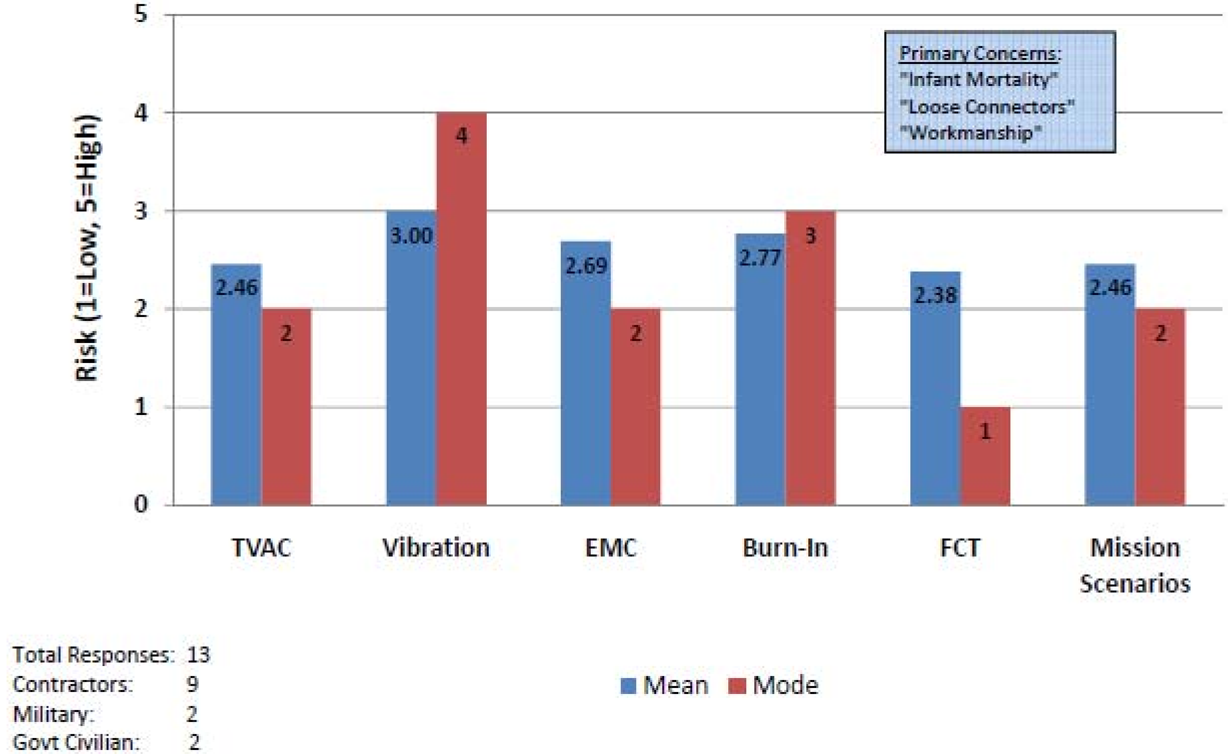

Figure 4. Risk of Eliminating System-Level Tests

With 1 being the lowest risk and 5 being highest risk, the participants largely agreed that eliminating any of the above tests introduced a moderate level of risk. There is of course risk associated with eliminating any test, but the ORS office may deem "moderate risk" acceptable for an urgent need spacecraft. Of these tests, however, eliminating vibration testing was considered most risky. The vibration test validates the primary modes of the spacecraft which is a design property and as such could be validated through analysis or on a qualification model. Vibration testing could also precipitate workmanship errors like loose connections on wiring harness or structure. These errors could be mitigated through good assembly practices and quality assurance checks, but a short test (perhaps 1-axis versus all 3) could be performed within the rapid call-up window to verify connections are solid.

The second highest risk was assigned to elimination of long burn-in testing. Burn-in tests are used to detect infant mortality and intermittent failures. The burn-in could be conducted at the component level and through intermittent functional tests while in inventory.

Eliminating electromagnetic compatibility testing (EMC) constitutes the third highest risk as seen by survey participants. EMC tests detect RF interference and are most important for RF-sensitive payloads. In the case of an RF-sensitive payload, the EMC tests could be part of the payload integration, test, and calibration activities. For other payloads, the EMC tests may not be necessary as workmanship is hard to detect and the design can be previously qualified and supported by analysis. If a workmanship mistake occurred such as not installing or damaging RF components, the bus functional tests should catch the errors.

Spacecraft Modularity

The following questions were asked in Surveys 1 and 2:

What level of modularity do you think should be applied to Responsive Spacecraft?

a. Very Modular – Components on shelf
b. Somewhat Modular – Subsystems on shelf
c. Not at all Modular – Fully-assembled bus on shelf

What level of modularity should be applied to Responsive Payloads?

a. Very Modular – Pieces on shelf
b. Somewhat Modular – Partially-assembled, uncalibrated payloads on shelf
c. Not at all Modular – Fully-assembled, calibrated payloads on shelf

14 surveys were collected this day, and there were 15 answers to the question of Bus Modularity and 13 answers to the question of Payload Modularity. The breakdown of responses can be found in Figures 5 and 6.

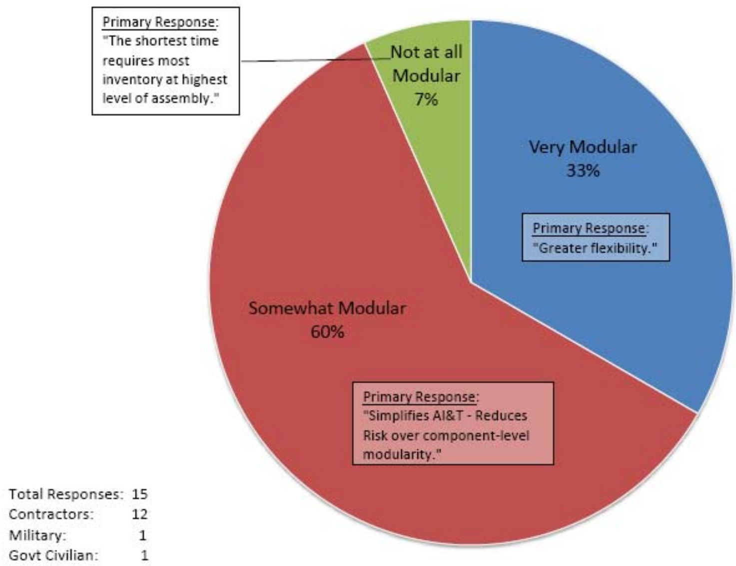

Figure 5. Modularity of Responsive Spacecraft Buses

The desire to balance flexibility with responsiveness is clear in the responses regarding modularity of the spacecraft bus. Most participants indicated that component-level modularity is too drastic and will complicate/elongate AI&T. It is interesting that a small percentage chose "Not at all Modular." While low modularity does provide for a faster AI&T timeline, it may also complicate on-shelf testing requirements and increase required inventory. If inventory is not increased, flexibility in the capabilities that can be delivered will be reduced.

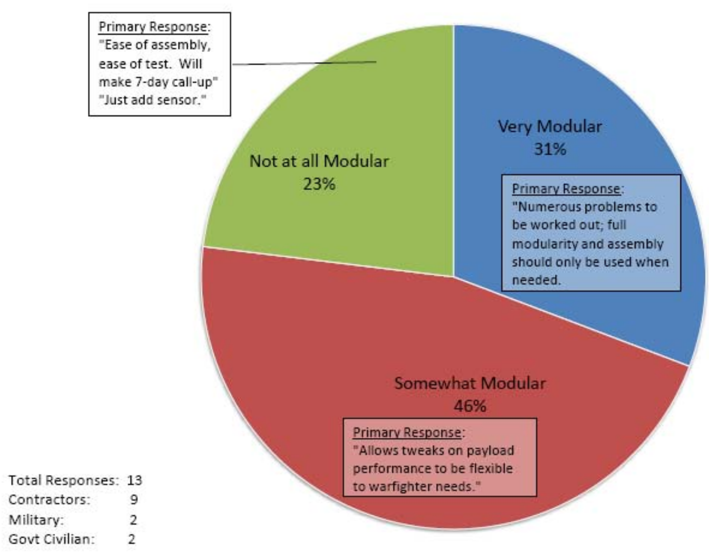

Figure 6. Modularity of Responsive Spacecraft Payloads

Here again the balance of flexibility and fast response is chosen for modularity of payloads. While the same percentage of responses indicated "Very Modular" as did in the case of bus modularity, the percentage of "Not at all Modular" increased. This could be directly related to the calibration requirements of a sensor that would make a 6 day call-up impractical. Fully integrated sensor packages ready to be integrated to the bus is most similar to the U-2 concept for space. However, the majority of the responses indicated "Somewhat Modular" is best, allowing updates to the payload as technology advances or as needs change.

Custom Bus vs. Common Bus Architecture

The following questions were asked in Survey 3:

Which end of the spectrum should the ORS Office be investigating for Responsive Space Satellites:

a. Common Bus Architecture – One bus works for all ORS missions
b. Custom Bus Architecture – The bus is customized for the mission, within the 6-day call-up window

6 surveys were collected this day, and there were 6 answers to the question. The breakdown of responses can be found in Figure 7.

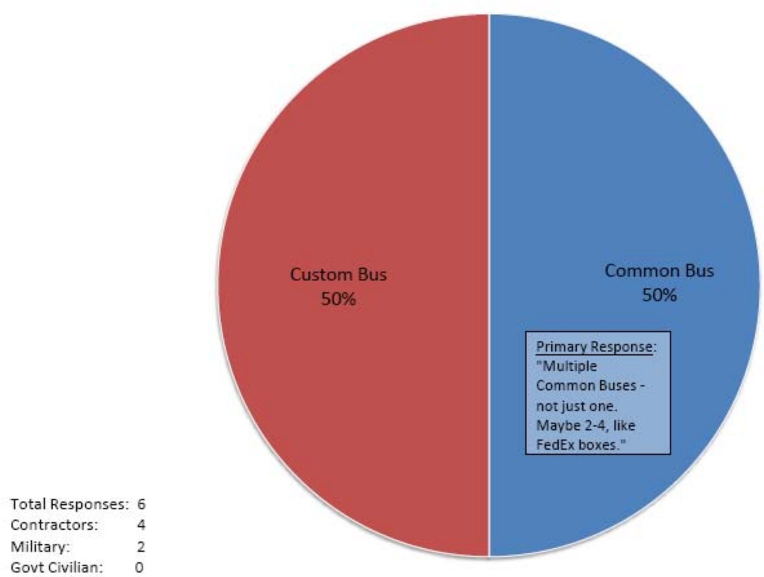

Figure 7. Custom Bus vs. Common Bus Architecture

It is interesting that the divide between Custom Bus and Common Bus Architecture is equal. That may suggest that the answer is in the middle somewhere, which is perhaps intuitive. A very intriguing suggestion received was storing multiple common buses for varying mission types. The participant with this suggestion likened it to FedEx's multiple sized boxes. This could also be likened to the operational military and tied to the U-2 concept: U-2's, UAV's, EP-3's and F-16's all carry different sensor packages based on their capability and mission objectives. This could also be a model for Responsive Spacecraft.

Component Retest Rate
The following questions were asked in Survey 3:

How often do you believe components/subsystems should be re-tested for functionality while in storage?

a. Never
b. Yearly
c. Twice Yearly
d. Monthly
e. Other

6 surveys were collected this day, and there were 6 answers to this question. The breakdown of responses can be found in Figure 8

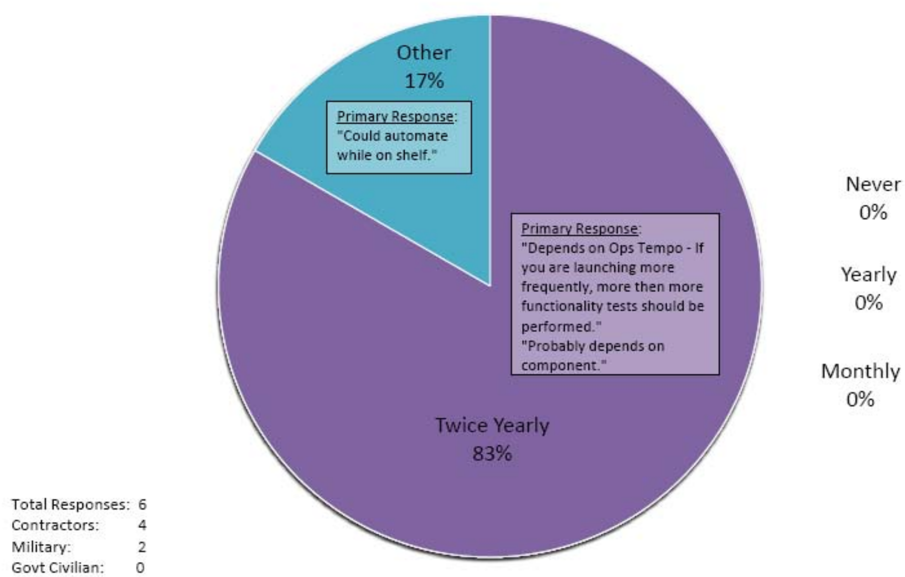

Figure 8. Component Retest Rate

The rationale for only low level system testing conducted during a 6 day call-up rapid AI&T is based upon the assumption that components (or subsystems) are separately verified for functionality and performance. If components sit on a shelf for some period of time, they may start to fail, perhaps from age, latent failure, or environmental degradation. Therefore, there should be a rechecking of these components at some interval, to ensure best chance of success at call-up. Most participants in this question indicated that components should be tested twice yearly. However, this number may vary greatly based on Ops Tempo and component lifetime concerns.

Personnel Retrain/Exercise Rate
The following questions were asked in Survey 3:

How often do you believe Rapid AI&T personnel should retrain or conduct exercises to maintain readiness for an urgent need call-up?

a. Continuously
b. Yearly
c. Twice Yearly
d. Monthly
e. Other

6 surveys were collected this day, and there were 6 answers to this question. The breakdown of responses can be found in Figure 9.

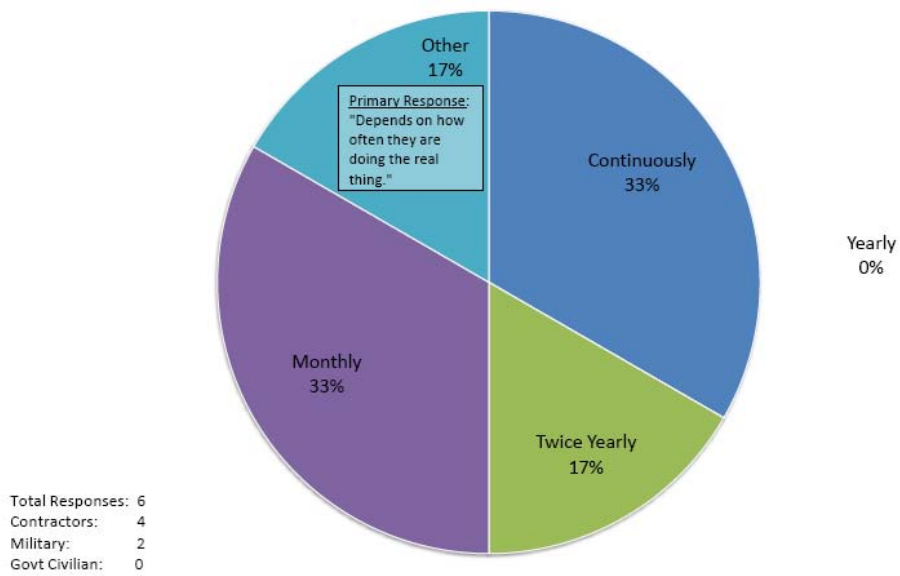

Figure 9. Personnel Retrain Rate

The respondents in this survey felt that AI&T personnel should be either continuously or nearly continuously retraining or conducting exercises to maintain proficiency and readiness for a rapid call-up scenario. This philosophy would have to be weighed against the risk of damaging or exceeding lifetime of flight hardware used in the exercise. Another option could utilize test articles for exercises, but varying configurations would be vital in the retrain process and may be difficult with a limited number of test parts.

Rapid AI&T Facility Considerations
The following question was asked in Survey 3:

What factors would you consider when designing a Responsive Space Assembly, Integration, and Test facility?

6 surveys were collected this day, and there were 6 answers to this question. The responses can be found in Table 1.

Table 1. Rapid AI&T Facility Considerations

It has to be about your process control and creating a process that minimizes assembly and workmanship risk.
Work Flow, accessibility to SC transport, classification.
Test equipment and/or diagnostics capability - there will be issues! Need to be able to isolate the root cause quickly.
Standard Robust Interfaces, architecture flexibility.
All testing equipment in house with spares of long lead components most likely to break.
Storage space with power and network, environmental, all test equipment available as needed.

These suggestions can help ORS design a facility conducive for Tier-2 response.

PnP Standards in Industry
The following question was asked in Survey 3:

Do you envision Plug-and-Play interface standards being applied across the U.S. Spacecraft Industry? World-wide?

6 surveys were collected this day, and there were 6 answers to this question. The responses can be found in Table 2.

Table 2. PnP Standards in Industry

Yes, if standards can be matured to a point where they are not in constant state of flux and there is a business case to use them.
Not in near term - too untested. Perhaps eventually in U.S. World-wide much more difficult to imagine due to security, tech transfer.
Standards - iffy. Modularity - more likely
Yes.
Yes, especially with ASIMS.
Yes, it needs to in order for the business case to work. May not be only PnP but exceptions should not be the rule.

These comments indicate that PnP is an accepted technology standard in the industry with hopes of becoming more mainstream. PnP should continue to be a basis for Tier-2 satellites.

Conclusion
In an effort to gain suggestions and lessons from the space community, short surveys were given at the RS7 Conference. Questions were posed in the areas of mission design, launch operations, test requirements, facility layout, logistics and training. The participants, with varied roles and experiences in the community, provided suggestions and insight that could be very useful to the ORS office in determining the concept of operations for the future Chileworks facility.

Appendix E. Lessons Learned

This is a full list of lessons learned/observations/suggestions compiled from various Rapid AIT team members and observers after each trial.

Spacecraft Design

- Design S/C and components for testability.
- Use larger or captive fasteners on connectors.
- Use Connector Keying whenever possible.
- Nothing should be Hard-Coded or Hand-Coded.
  - Flight software should not be designed for a specific set of components or vehicle configuration
  - Solar Array orientation hard-coded in ADCS SW
  - Configuration Files do exist on PnPSat-1 but are hand-coded
- Thermal Blanket and Tape customization method is needed
  - Utilized automated cutting table in Trial 3 – tapes cut in few hours, installed in fraction of time.
  - Some trade-off in coverage as shapes are simplified
  - Previously fabricated blankets used for all trials
- S/C should have a dual capability for hard line and RF command/telemetry.

Facility and Equipment

- Test equipment should be located inside the clean room.
- A variety of connector covers and cable lengths should be available in assembly facility.
  - Should be included in parts list, like number/size of bolts, washers
- Display procedures and drawings on monitors in clean room.
  - Eliminates paper and pen FOD
  - Provides situational awareness to all members of team
- Facility power is critical:
  - Accurate map of available circuits and ratings
  - Plan GSE load distribution to prevent tripping breakers
  - Power strips are not adequate without load distribution plan
- Ensure software on all equipment is up to date and compatible.
  - AFRL cutting table had old version of SolidWorks, recreated drawings to get tapes made within week.
- For maximum flexibility, use adjustable GSE.
  - For example, RF test equipment should avoid the use of fixed attenuators or items tuned for specific frequencies.
- Design Integration Stand for ease of assembly and with multiple functions.
  - Measurement of vehicle mass and CG can be performed by a support stand with integrated load cells.
  - Integration Stand should provide adequate access to all panels, even the bottom.
- Replacement/Spare GSE parts must be stocked/available.

  - Assumption that common parts like computers will be available is false – updated PC hardware and software may not be compatible. (XP vs. Vista)
  - GSE should be regularly tested/inspected/calibrated.
  - Cover unused connectors to prevent failures.
- Lifting interface should be standardized across ORS vehicles so that a standard lifting fixture could be designed with adjustable supports and leveling capabilities

Personnel and Processes

- Strict AI&T discipline must be enforced.
  - Cover unused connectors (GSE and Flight HW), follow procedures, do not alter scripts or GSE setup without QA-approved redline (not verbal).
- Configuration Control is a full-time job and should not be left to engineers.
  - Utilize inventory control SW
- Number of personnel is not as critical as the correct mix of skill sets
  - Personnel should be trained in specific areas of expertise and perform only those operations to maintain proficiency and have clearly defined roles.
- Assembly and Test Procedure format requires investigation.
  - Assembly drawing vs. assembly procedure
  - Should be automated, to eliminate human cut and paste errors.
  - Ideal level of detail seems to be drawing plus table of components per panel – includes number of fasteners, torque value, endpoint connector
- A standard electronic ICD should be delivered with components into inventory.
  - Items such as number of fasteners, torque, required equipment, etc. should be easily parsed into assembly procedures.
  - Items such as operations considerations, telemetry value definitions, etc. should be easily parsed into operations manuals.
  - Should include xTEDS and ASIM code.
  - These files will also be used to create configuration files, which are currently required to sync the ground station with the S/C configuration.
- Determine contingency procedures – troubleshoot vs. ignore vs. replace component vs. remove article from assembly line and start over.
- Automated test scripts should be "Go/NoGo" type with adequate limit checking.
- Communication/situational awareness between operations site, S/C AIT site, and launch site requires more investigation.

Payload Integration

- Payload test facility should be collocated with the S/C AIT facility, and should include test equipment with similar electrical and mechanical interfaces to the S/C bus.
- Payload modules should be stored in either a clean room or nitrogen purged containers.
- The S/C AIT facility should have a fully capable optical test station in the integration clean room.
- Alignment, calibration, and performance activities required after payload integration to S/C bus requires more investigation.

- If a performance test is required after integration, optical test equipment should be used for imaging rather than distant scenes due to the focal length of space-based imagers. Steering mirrors or mobile test stand can be used to project a scene onto the payload optics.

- The payload & bus should be designed to enable real-time image acquisition during integration and testing. Limitations on the data rate on the desktop SPA and the bus delayed the payload configuration and the post-integration payload functional tests.
- The nature of the rapid call-up scenario did not limit payload testing capabilities.
  - All of the possible configurations had been fully tested prior to being accepted into inventory. Had a new configuration been requested, more time would be required for testing.

Ground System and Operations

- There should be a standard command/telemetry naming convention between all ground systems and components.
  - Mnemonics should be unique, and not easily confused.
- Current xTEDS don't provide enough information to automate generation of displays.
  - Currently done manually, which requires knowledge of S/C and component operations.
- Operations procedures should be predefined and included in the electronic Standard ICD.
- Operations rehearsals can be executed concurrently with AIT and launch site activities using simulations.
- When S/C AIT is complete, operations team should work with AIT team to do combination Factory Compatibility Test and Dress Rehearsal.
  - Use operations ground system and flight-ready S/C in an RF end-to-end configuration.
- Commanding interface should provide knowledge of every command sent to S/C.
  - Procedures should be automated as much as possible to most efficiently utilize contact time.
  - Scripts should prompt operator at key steps.
  - Limit checking, timeouts can allow script to continue, but should update operator at every step.
  - Graphical representation of script flow has been successfully used previously.
- Navigating a file structure to find appropriate command is not efficient and too cumbersome. A more user-friendly command look-up interface should be investigated.
- The ground station should include an indicator of whether S/C telemetry is received.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704–0188*

1. REPORT DATE (DD–MM–YYYY)	2. REPORT TYPE	3. DATES COVERED *(From — To)*
25-03-2010	Master's Thesis	March 2009-March 2010

4. TITLE AND SUBTITLE Assembly, Integration, and Test Methods for Operationally Responsive Space Satellites	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Lisa Baghal	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/ENY) 2950 Hobson Way WPAFB OH 45433-7765	8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/GAE/ENY/10-M01
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Operationally Responsive Space Office Charles Finley 3548 Aberdeen Ave SE, Kirtland AFB, NM 87117 505-853-6663	10. SPONSOR/MONITOR'S ACRONYM(S) ORS 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Current government and industry standards in spacecraft testing result in an Assembly, Integration, and Test (AIT) timeline greater than six months. These standards will not support the vision of Operationally Responsive Space (ORS) to deploy a satellite within six days to fill an urgent need. Using the Air Force Research Laboratory's Plug-and-Play Satellite (PnPSat), multiple Rapid AIT trials were conducted. By exercising the AIT process with various spacecraft configurations and personnel, methods for reducing or modifying traditional testing regimen were investigated.

15. SUBJECT TERMS
Spacecraft Assembly, Integration and Test; Operationally Responsive Space

16. SECURITY CLASSIFICATION OF: UNCLASSIFIED			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Lt Col Eric Swenson
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include Area Code)
U	U	U	UU	141	(937)255-3636, ext 7201